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CARNEGIE INSTITUTION OF WASHINGTON DEPT. OF TERRESTRIAL MAGNETISM SCIENTIFIC RESULTS OF CRUISE VII OF THE CARNEGIE, 1928-1929 CHEMISTRY

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DEPARTMENT OF TERRESTRIAL MAGNETISM
J. A. Fleming, Director

Scientific Results of Cruise VII of the CARNEGIE during 1928-1929
under Command of Captain J. P. Ault

CHEMISTRY—I

Chemical Results of the Last Cruise of the Carnegie

HERBERT W. GRAHAM

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PREFACE

Of the 110,000 nautical miles planned for the seventh cruise of the nonmagnetic ship Carnegie of the Carnegie Institution of Washington, nearly one-half had been completed on her arrival at Apia, November 28, 1929. The extensive program of observation in terrestrial magnetism, terrestrial electricity, chemical oceanography, physical oceanography, marine biology, and marine meteorology was being carried out in virtually every detail. Practical techniques and instrumental appliances for oceanographic work on a sailing vessel had been most successfully developed by Captain J. P. Ault, master and chief of the scientific personnel, and his colleagues. The high standards established under the energetic and resourceful leadership of Dr. Louis A. Bauer and his coworkers were maintained, and the achievements which had marked the previous work of the Carnegie extended.

But this cruise was tragically the last of the seven great adventures represented by the world cruises of the vessel. Early in the afternoon of November 29, 1929, while she was in the harbor at Apia completing the storage of 2000 gallons of gasoline, there was an explosion as a result of which Captain Ault and cabin boy Anthony Kolar lost their lives, five officers and seamen were injured, and the vessel with all her equipment was destroyed.

In 376 days at sea nearly 45,000 nautical miles had been covered (see map, p. iv). In addition to the extensive magnetic and atmospheric-electric observations, a great number of data and marine collections had been obtained in the field of chemistry, physics, and biology, including bottom samples and depth determinations. These observations were made at 162 stations at an average distance apart of 300 nautical miles. The distribution of these stations is shown in the map, which delineates also the course followed by the vessel from Washington, May 1, 1928, to Apia, November 28, 1929. At each station, salinities and temperatures were obtained at depths of 0, 5, 25, 50, 75, 100, 200, 300, 400, 500, 700, 1000, 1500, etc., meters, down to the bottom or to a maximum of 6000 meters, and complete physical and chemical determinations were made. Biological samples to the number of 1014 were obtained both by net and by pump, usually at 0, 50, and 100 meters. Numerous physical and chemical data were obtained at the surface. Sonic depths were determined at 1500 points and bottom samples were obtained at 87 points. Since, in accordance with the established policy of the Department of Terrestrial Magnetism, all observational data and materials were forwarded regularly to Washington from each port of call, the records of only one observation were lost with the ship, namely, a depth determination on the short leg between Pago Pago and Apia.

The compilations of, and reports on, the scientific results obtained during this last cruise of the Carnegie are being published under the classifications Physical Oceanography, Chemical Oceanography, Meteorology, and Biology, in a series numbered, under each subject, I, II, and III, etc.

A general account of the expedition has been prepared and published by J. Harland Paul, ship's surgeon and observer, under the title The last cruise of the Carnegie, and contains a brief chapter on the previous cruises of the Carnegie, a description of the vessel and her equipment, and a full narrative of the cruise (Baltimore, Williams and Wilkins Company, 1932; xiii + 331 pages with 198 illustrations).

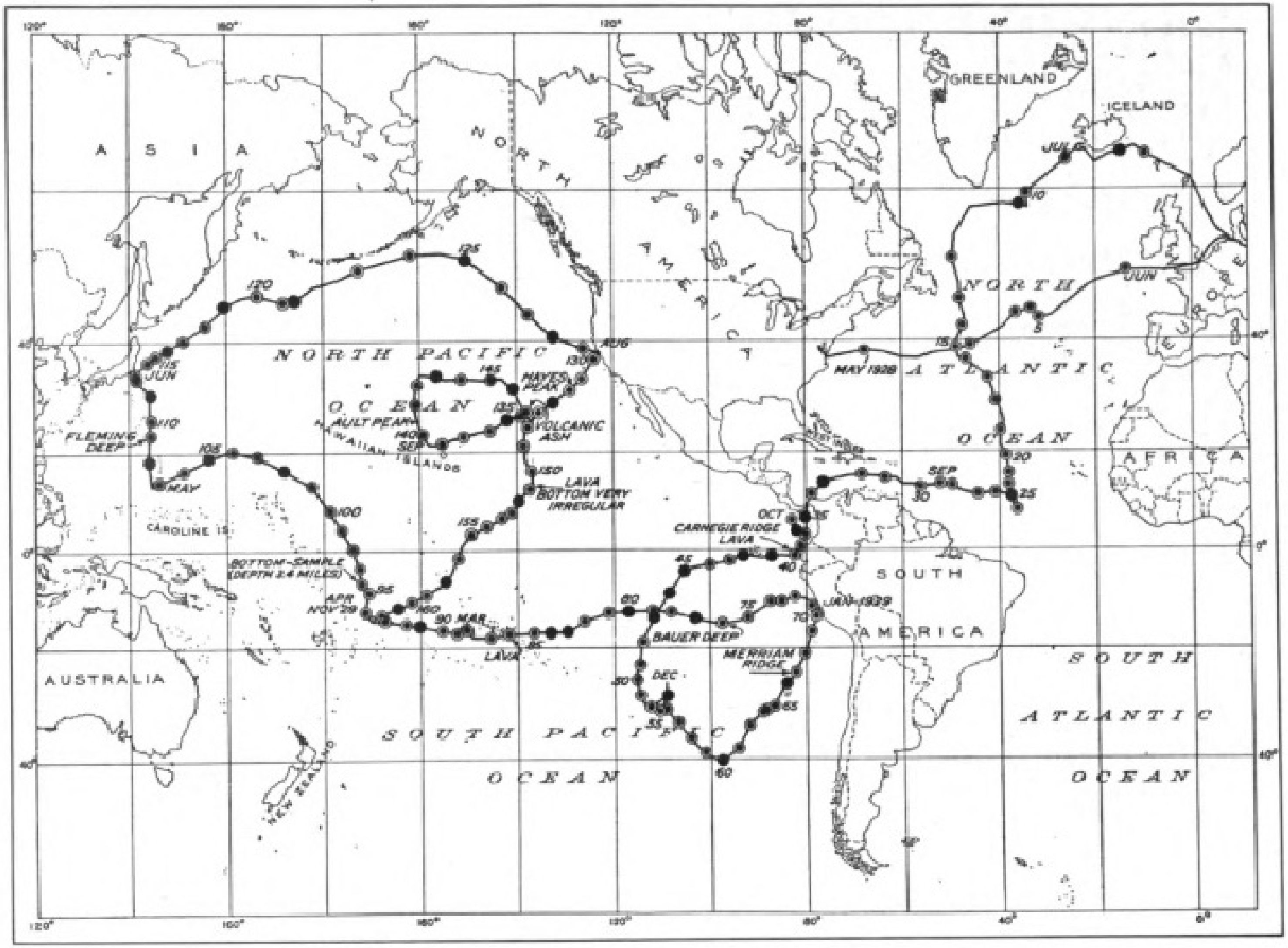
The preparations for, and the realization of, the program would have been impossible without the generous cooperation, expert advice, and contributions of special equipment and books received on all sides from interested organizations and investigators both in America and in Europe. Among these, the Carnegie Institution of Washington is indebted to the following: the United States Navy Department, including particularly its Hydrographic Office and Naval Research Laboratory; the Signal Corps and the Air Corps of the War Department; the National Museum, the Bureau of Fisheries, the Weather Bureau, the Coast Guard, and the Coast and Geodetic Survey; the Scripps Institution of Oceanography of the University of California; the Museum of Comparative Zoölogy of Harvard University; the School of Geography of Clark University; the American Radio Relay League; the Geophysical Institute, Bergen, Norway; the Marine Biological Association of the United Kingdom, Plymouth, England; the German Atlantic Expedition of the Meteor, Institut für Meereskunde, Berlin, Germany; the British Admiralty, London, England; the Carlsberg Laboratorium, Bureau International pour l'Exploration de la Mer, and Laboratoire Hydrographique, Copenhagen, Denmark; and many others. Dr. H. U. Sverdrup, now Director of the Scripps Institution of Oceanography of the University of California, at La Jolla, California, who was then a Research Associate of the Carnegie Institution of Washington at the Geophysical Institute at Bergen, Norway, was consulting oceanographer and physicist.

In summarizing an enterprise such as the magnetic, electric, and oceanographic surveys of the Carnegie and of her predecessor the Galilee, which covered a quarter of a century, and which required cooperative effort and unselfish interest on the part of many skilled scientists, it is impossible to allocate full and appropriate credit. Captain W. J. Peters laid the broad foundation of the work during the early cruises of both vessels, and Captain J. P. Ault, who had had the good fortune to serve under him, continued and developed that which Captain Peters had so well begun. The original plan of the work was envisioned by L. A. Bauer, the first Director of the Department of Terrestrial Magnetism, Carnegie Institution of Washington; the development of suitable methods and apparatus was the result of the painstaking efforts of his co-workers at Washington. Truly, as was stated by Captain Ault in an address during the commemorative exercises held on board the Carnegie in San Francisco, August 26, 1929, "The story of individual endeavor and enterprise, of invention and accomplishment, cannot be told."

Dr. H. W. Graham, chemist and biologist on board the Carnegie from August 1929 until the loss of the vessel at Apia, Samoa, in November 1929, was assisted in the preparation of the present chemical report by Dr. E. G. Moberg of the Scripps Institution of Oceanography. Dr. Moberg was guest chemist on the Carnegie from August through September 1929.

This report on hydrogen ions, phosphate, silicate, and dissolved oxygen of sea water represents the most extensive investigation bearing on such matters ever undertaken in the Pacific Ocean. One hundred and twenty-eight stations were occupied in this Ocean. Considerable research in the chemical field had been undertaken in the Atlantic Ocean on earlier expeditions. Nevertheless, the thirty-four stations occupied by the Carnegie were in

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OCEANOGRAPHIC STATIONS, CRUISE VII OF THE CARNEGIE, 1928-29

(At the 35 stations marked ● true sea-water samples were also obtained for salinity calibrations)

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the central North Atlantic and the Caribbean Sea--regions not previously investigated. The data and their discussions are valuable contributions to our knowledge of the chemical conditions in different regions at various levels.

It should be noted that this report contains no references to literature published later than the early part of 1935, at which time the final revision of the manuscript was made. It is realized, however, that more recently the results of a number of oceanographic investigations dealing with both the Atlantic and the Pacific oceans, as well as with adjacent marine regions, have been published. As a consequence of these recent investigations it is possible that some of the generalizations or conclusions based on the Carnegie and earlier data will need to be modified, but it is felt that the results of the observations and analyses made by the Carnegie are reliable and comparable with those subsequently reported.

The present volume is the tenth in the series "Scientific results of cruise VII of the Carnegie during 1928-1929 under command of Captain J. P. Ault."

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SCOPE AND METHODS OF THE CHEMICAL INVESTIGATIONS

INTRODUCTION

The chemical program of the Carnegie was organized primarily with a view of gaining information concerning the nature of the biological environment in the regions traversed, although some of the chemical data obtained can be used as indicators of water movements. The chemical constituents determined include hydrogen ions, phosphate, silicate, and dissolved oxygen. Salinities were also determined but, since these were used principally for the study of the physical properties of the water, the discussion of them has been included in another report.

It has long been known that the major constituents of the dissolved salt in sea water occur in constant proportion, and that their quantities may be computed from the salinity or from one of its components--the chloride for example. Many of the minor constituents, especially those involved in biological activities, do not occur in constant proportion to the total salt, and their concentration, as in the case of phosphate, may vary by several hundred per cent. Among the substances that play an important role in the metabolic cycle of the sea are nitrates, phosphates, silicates, carbon dioxide, and oxygen. The first four are extracted from the water by plants and liberated in the final decomposition of organic remains. Carbon dioxide is absorbed by plants and oxygen is liberated during photosynthesis whereas the reverse occurs during the respiration of plants and animals. Because of their intimate relation to the life in the sea, and because of the great variability in their quantities, it is essential to determine these substances in various localities and at various depths in order to obtain an adequate picture of the biological environment in any part of the sea.

Aside from their importance in biological studies and as indicators of water movements and the origin of water masses, some of the substances determined assume a prominent part in geological processes taking place on the sea bottom. For example, silicate relationships are involved in the deposition of diatom shells; and pH relationships are involved in the solubility of calcium carbonate in sea water.

HISTORICAL

Prior to the last cruise of the Carnegie several of the chemical substances concerned with the growth of organisms had been investigated in various parts of the Atlantic, but for the Pacific there was little information available. This was particularly true for the open Pacific for which information was almost entirely lacking. The earliest records of any chemical investigations in the Pacific are those of the Challenger expedition in 1873 to 1876 (Dittmar, 1884). The reports of this expedition are classics in the pioneer study of the chemistry of sea water, as well as of other phases of oceanography, but its work was concerned chiefly with the major saline components of sea water. Dissolved oxygen was determined on a few isolated water samples but the results are not adequate for any general conclusions. The Planet (Brennecke, 1909) in 1906 to 1907 made some chemical investigations of the water below the surface between New Guinea and Hong Kong. A. G. Mayor (1919, 1922) determined the hydrogen-ion concentration of the surface water between San Francisco and the Hawaiian and the Samoan islands. The Dana (Schmidt, 1925, 1929) determined the dissolved oxygen at various depths in the Gulf of Panama in 1922. Ito (1928) in 1926 determined the hydrogen-ion concentration of water from various levels between New Guinea and Japan. In certain coastal areas more complete investigations had been carried out: for example, in the Strait of Georgia by the Pacific Biological Station of the Biological Board of Canada; in the Puget Sound region by the University of Washington; along the coast of southern California by the Scripps Institution of Oceanography of the University of California; and off Monterey cooperatively by the Hopkins Marine Station of Stanford University, the Museum of Comparative Zoology of Harvard University, the Scripps Institution of Oceanography, and the California Division of Fish and Game. Most of these localities cannot be considered as representing the open Pacific, however, and the chemical conditions in virtually the whole of this ocean were practically unknown until investigated by the Carnegie.

Subsequent to the Carnegie's cruise, further work has been carried out in the coastal areas mentioned by the Japanese in the waters adjacent to Japan, and by the Great Barrier Reef expedition in the Great Barrier Reef region of Australia. The following expeditions and institutions have investigated certain chemical conditions in the open Pacific: the Willebrord Snellius expedition in the Dutch East Indies; the Dana expedition from Panama to the East Indies; the Japanese training ship, the Sintoku Maru, from Kobe to San Diego; the University of Washington in the Gulf of Alaska and, in cooperation with the United States Navy, in the Bering Sea; and the Scripps Institution of Oceanography in cooperation with the United States Navy off the coast of Central America and from the Aleutian Islands to the Hawaiian Islands. To the results of most of these investigations reference will be made in the Carnegie chemistry reports.

The Carnegie's investigations in the Pacific are by far the most extensive ever undertaken in this ocean. One hundred and twenty-eight stations were occupied and samples for chemical analyses were taken from about twenty levels at each station, extending from the surface usually to several thousand meters. At nearly all the stations phosphate and hydrogen ions were determined and at the last thirty-three stations also silicate and dissolved oxygen. As a result, a fairly complete picture was obtained of the distribution, vertical and horizontal, of plant nutrients in a large part of the North Pacific as well as in the tropical and southeastern South

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Pacific, and of the oxygen content of the surface and the subsurface water of a large part of the open Pacific.

In the Atlantic the Carnegie occupied only thirty-four stations. Hydrogen ions and phosphates were determined at various levels at all stations and dissolved oxygen at two stations. Although the data obtained are not extensive when compared with those obtained in the Pacific, they constitute an important contribution to our knowledge of the chemical conditions in regions not previously investigated, namely, the central North Atlantic and the Caribbean Sea. These data became particularly interesting when compared with those obtained by others in both the North and South Atlantic.

On board the Carnegie, H. R. Seiwell had charge of the chemical investigations in the Atlantic and from Panama to Samoa in the Pacific (stations 1 to 93); J. H. Paul from this point to Yokohama and thence to San Francisco (stations 94 to 129); and H. W. Graham from San Francisco to the termination of the cruise at Samoa (stations 130 to 162). Between San Francisco and Honolulu, E. G. Moberg of the Scripps Institution of Oceanography, who was a guest investigator on board, made some of the analyses, especially of oxygen.

METHODS

Phosphate

For the determination of phosphate, use was made of the colorimetric method of Denigès (1920, 1921) as adapted for sea water by Atkins (1923a, 1925). This method depends on the formation of an intense blue, on the addition of certain reagents to a solution containing phosphate, the intensity of the color being in direct relation to the quantity of dissolved phosphate. To 100 ml of the sample to be analyzed, were added 1 ml of a solution consisting of one part of 10 per cent ammonium molybdate and three parts of 50 per cent (by volume) sulphuric acid, and one or two drops of stannous chloride solution freshly prepared from 0.1 gm of tin dissolved in 2 ml of hydrochloric acid, in the presence of a small quantity of copper sulphate, and made up to 10 ml with distilled water. The blue color appearing in the sample was matched against that of a standard phosphate solution similarly treated. For this comparison the sample and standard were placed in glass tubes about 300 mm long and about 25 mm in diameter and graduated in 125 units. These tubes were viewed in a colorimeter constructed to throw diffused light through the columns of liquid when standing in a vertical position and the levels of the liquids in the tubes were adjusted until both showed the same intensity of the blue color. By using appropriate standards, the difference in the scale readings of the two tubes was kept to within twenty-five scale divisions and usually to much less.

The working standards used were made up from a stock solution of potassium dihydrogen phosphate preserved with toluene. A supply of this solution, which was thought sufficient to last until the Carnegie's arrival in a home port, was prepared before the start of the cruise. This supply was almost exhausted on arrival in Japan (station 112), however, where a temporary standard was made up, calibrated with the old, and used for stations 113 to 129. A fresh standard, prepared at the Scripps Institution of Oceanography by Moberg, was used from San Francisco until the end of the cruise (stations 130 to 162). The old standards were checked against this standard and were found to have suffered no deterioration.

Those who are familiar with this method will realize that the accuracy of the results, as expressed in per cent, decreases with decrease in concentration of phosphate in the samples analyzed and that values of 5 mg PO_4 per cubic meter or less should be regarded as indicating merely the order of magnitude. For "salt error" no correction was applied, and consequently our results are comparable with nearly all the results of phosphate studies of sea water reported before 1930.

The phosphate values are expressed as milligrams of PO_4 per cubic meter, because at the time the data were computed and tabulated this was the most commonly used method. Many of the earlier data found in the literature are given as P_2O_5, whereas many of those published later are expressed as P or, more recently, as milligram atoms per kilogram or cubic meter.

Silicate

Silicate was determined by the method of Dienert and Wandenbulcke (1923) as modified by Atkins (1923a). This is a colorimetric method, similar to that used for phosphate. On the addition of certain reagents to a silicate solution, a yellow color like that of a picric acid solution is developed. In making the determination, 2 ml of a 10 per cent solution of ammonium molybdate and 6 drops of a 50 per cent (by volume) solution of sulphuric acid were added to a 100 ml sample of sea water. In the same colorimeter used for the phosphate determination, the sample thus treated was compared with a picric acid standard of a concentration such that the scale readings of the two tubes differed by less than 25 units. The standards were prepared as directed by King and Lucas (1928), who found that a solution of 25.6 mg of dry picric acid per liter has a color corresponding to that of a silicate solution equivalent to 50 mg SiO_2 per liter.

Samples for the determination of silicate were drawn from the Nansen bottles into "citrate of magnesia" bottles and analyzed the following day. Experiments carried out at the Scripps Institution of Oceanography have shown that sea water may be stored for at least this long in bottles of this type, if well seasoned, without undergoing any measurable increase in the silicate content. In order to insure that the bottles used on the Carnegie would not give off silicate to the water, they were filled with sea water and left standing for several weeks. Nevertheless, the water stored in a few of these bottles consistently gave results that obviously were too high. These bottles were finally discarded and the results obtained from water stored in them have been marked "rejected" in the tables and have not been included in the graphs.

The results of silicate determinations are expressed as mg SiO_2 per cubic meter and, as in the case of phosphate, correction for salt error has not been made.

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Oxygen

Dissolved oxygen was determined according to the method of Winkler (1888). The water to be analyzed was drawn from Nansen bottles (Oceanogr. 1-A, p. 3)[1] through a glass tube into green glass, patent-stoppered bottles having a capacity of approximately 100 ml and calibrated by weighing distilled water to 0.1 gram. When drawing a sample, enough water was allowed to overflow to thoroughly flush out any air-contaminated water. As soon as the bottle was filled with the sample, manganous chloride and a sodium hydroxide-potassium iodide mixture was added. When the resulting precipitate had settled, hydrochloric acid was added. The samples were titrated within a few hours after collecting. The N/100 thiosulphate solution used for the titration was standardized against N/100 potassium dichromate solution at every second oceanographic station, that is, every four days. The burette was read to 0.05 ml and the authors believe that the results are accurate to about 0.03 ml per liter. The results are expressed in milliliters per liter and in percentage of saturation. In computing the latter, the saturation values given by Jacobsen (1905) were used. His values are slightly below those of Fox (1909), and Whipple and Whipple (1911). For temperatures higher than those included in Jacobsen's table (0° to 25°), the saturation values were obtained by extrapolation and by comparison with the tables of Fox and Whipple and Whipple.

Hydrogen-ion Concentration

The hydrogen-ion concentration was determined colorimetrically by means of a double-wedge comparator similar to one used at the Scripps Institution of Oceanography for a number of years (Moberg, 1926a). The comparator consists essentially of a rectangular glass box divided diagonally by a vertical glass partition into two wedge-shaped compartments, the dimensions being approximately those given by Barnett and Barnett (1920), namely, 35 cm long and 1.5 cm wide. In making a determination, one of the compartments is filled with an acid-indicator solution and the other with an alkaline solution of the same indicator. When viewed horizontally, the comparator then presents the entire color range of the indicator, with the center representing the hydrogen-ion concentration of the half-transformation point of of the indicator. A scale attached to the comparator and graduated into one hundred divisions thus gives the percentage of transformation or apparent dissociation of the indicator. From the scale reading and the indicator constant, the corresponding degree of indicator transformation and hence the pH may be computed according to the following equation:

$$pH = pK - \log \frac{X}{100 - X}$$

where pK is the negative logarithm of indicator constant and X is the scale reading.

After the addition of indicator to give the same concentration as in the wedges, the sample to be analyzed is placed in a small glass box having the same liquid diameter as the total of the two wedges. This box is placed above the large box, which is moved until the colors in the two match, and then the scale reading is taken. Both boxes are contained in a light-proof housing, and artificial light is used for illumination. The instrument used on the Carnegie, with special modifications required for use at sea, was designed by R. H. Seiwell. Cresol red was used as indicator and the value 8.14 was used for pK. This value previously had been determined by Moberg and agrees well with that obtained by Barnett and Barnett (1921), namely, 8.13. All the pH readings were corrected for salt according to Ramage and Miller (1925), the correction -0.27 being used for all Carnegie samples. The determinations of pH were made within a few hours after collecting the samples. Since the cruise of the Carnegie, Buch (1929) has shown that the pH of sea water changes slightly with the temperature, and that there is a similar change in the indicator constant. In the case of the Carnegie data, corrections for the temperature effect were not made. This, however, makes them comparable with most of the data previously published and, because the temperature values are available, corrections may be applied when desired.

PRESENTATION OF DATA

The results of the chemical investigations carried out by the Carnegie, together with those of the physical investigations, are presented in table 2 (I-B, pp. 183-257) and graphs 14 to 92 (I-B, pp. 16-55). The vertical and horizontal distribution of the chemical constituents are further shown by sections constructed along the path of the cruise. These correspond to the sixteen sections prepared by Sverdrup (I-B) to illustrate the distribution of temperature, salinity, and density. A chart showing the geographic positions of the sections is given in figure C1. Frequent reference to this chart, which shows the various stations included in each section, will be necessary for a clear understanding of the discussions to follow. The exact positions of these stations can be obtained from the tables and graphs previously referred to. In the discussions of the chemical data, each constituent is taken up separately and in the following order: phosphate, silicate, hydrogen-ion concentration, and oxygen.

For each chemical constituent, a brief description of its distribution along the various sections is given at the beginning of the discussion. These descriptions follow, in general, a discussion of the vertical distribution of the substance in question, the conditions being discussed in order from the surface downward. In examining the sections, it will be noted that the vertical distribution of the chemical substances usually follows that of the physical conditions, that is, certain more or less distinct layers or zones can be recognized. The zones included in the discussions are as follows.

1. The convection or surface layer, in which the conditions are relatively uniform with respect to depth because of mixing of the water caused by temperature changes, winds, and other agencies. This layer is usually less than 100 meters in thickness.

2. The transition zone or discontinuity layer, in which there is a rapid change from conditions prevailing in the convection layer to those characteristic of deep water.

[1] Oceanography I-A and I-B, volumes of the same series as the present volume, by H. U. Sverdrup, F. M. Soule, J. A. Fleming, and C. C. Ennis (1944), hereafter will be referred to in this report as I-A and I-B.

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3. Zones 1 and 2 correspond approximately to what Defant (1928) calls the troposphere, the stratum in which there is an active circulation with relatively large variations in temperature and salinity. Its lower limit corresponds, according to Sverdrup (1-A, p. 83), to the 10° isotherm. In the Pacific this is found at 500 to 650 meters below the surface.

4. The layer between the troposphere and the sea bottom, Defant designates as the stratosphere. Here the temperature and salinity changes are relatively small and the water movements are slow.

Since the water layers enumerated above are based on the distribution of the physical conditions, and since the latter do not always correspond to the distribution of chemical substances, the names of the layers are not always used in their strict physical sense but often to designate only the distribution of the chemical substances. The distribution of these, as will be shown later, is the result not only of physical forces but of biological agencies as well.

A brief description of the geographic sections, together with some of the outstanding hydrographic conditions encountered, including the thickness of the convection layer as determined by the depth to which uniform physical conditions were found, follows.

CARNEGIE SECTIONS: GEOGRAPHIC POSITIONS AND HYDROGRAPHIC CONDITIONS

Atlantic Ocean

Section I (Stations 24 to 13).--This is a more or less north and south section through the North Atlantic from the Grand Banks of Newfoundland to latitude 8° north. Station 13 is located on the Grand Banks, stations 14 to 16 are in the Western Atlantic Basin, stations 17 and 18 on the Atlantic Ridge, and stations 19 to 24 in the eastern basin. The center of this section is in the Sargasso Sea which is characterized by warm water of high salinity. This is centered at stations 18 and 19. To the north, at station 15, there is a convergence of the cold water of the Grand Banks and the warm Atlantic water. This is shown by the temperature and salinity charts to a depth of 1500 meters. The stations south of the Sargasso Sea are in the North Equatorial Drift. The Intermediate Antarctic Current from the south comes in at 700 meters and extends as far north as station 20. The convection layer is about 50 meters thick in the central part of the section and about 25 meters thick elsewhere.

Section II (Stations 34 to 25).--This section runs approximately east and west in the tropical North Atlantic along the parallel of about 12° north from Panama to 37° west longitude. Stations 34 to 31 are in the Caribbean Sea, stations 30 to 28 are in the western basin of the Atlantic, station 27 is on the Atlantic Ridge, and stations 25 and 26 are in the eastern basin. The stations in the eastern part of this section are in the North Equatorial Drift. Those in the western part are in the continuation of this drift into the Caribbean. In the salinity chart the Intermediate Antarctic Current is clearly seen coming in at the south at 700 meters and extending into the Caribbean beyond station 31. The convection zone throughout this section is about 25 meters thick.

Miscellaneous Atlantic Stations.--Stations 1 to 12 have not been utilized in the construction of vertical sections. Stations 1 to 6 were occupied at the beginning of the cruise when the apparatus and technique were being perfected so that the results at these stations may not be so accurate as at the later stations. The stations are located between the United States, the British Isles, Iceland, and Newfoundland.

Pacific Ocean

Section III (Stations 60 to 72 and 40 to 37).--This section lies in the southeastern Pacific. It begins at approximately latitude 40° south and longitude 100° west and runs north-northeast to the coast of Peru at latitude 17° south whence it continues northward to the Gulf of Panama. Stations 60 to 65, south of 30° south, are in a branch of the South Pacific East Drift which is an appreciable current to a depth of 300 meters. Stations 66 to 72, between latitudes 30° and 10° south, are in the northward-flowing Peruvian or Humboldt Current. Stations 39 to 37 are included in an anticyclonic movement in the Gulf of Panama. Stations 67 to 72 are in a region off the coast of Peru where upwelling occurs in the upper 300 meters. The intermediate water off the South American coast flows westward between 600 and 700 meters. In this section the thickness of the convection layer is variable, ranging from a few to 40 meters.

Stations 35 and 36.--Stations 35 and 36 in the Central American Bight were not included in any section. They are situated in the same latitude as that part of Section III which lies between stations 37 and 39 but are closer inland than the latter stations.

Section IV. (Stations 51 to 45).--This section is also in the southeastern Pacific, approximately north and south from latitude 29° south to latitude 5° south and between longitudes 115° and 105° west. In the northern part of the section the currents are westerly, in the southern part they are very indefinite with a possible easterly movement. The convection layer is somewhat thicker than in the last section. At station 48 it is 80 meters, at station 45 it exceeds 60 meters, but at station 51 it is less than 25 meters.

Section V (Stations 162 to 148 and 134 to 130).--This section runs northeastward from the Samoan Islands (latitude 14° south, longitude 168° west) to San Francisco (latitude 37° north). It cuts through several current systems. To the extreme northeast is the California Current, with upwelling within the upper 400 meters, off the coast of California. Stations 150 to 151 are in the westward-flowing North Equatorial Drift. Station 153 is in the most active part of the Equatorial Countercurrent, which is a swift current but extends only to a depth of 200 meters. Stations 154 to 156 are south of the most active part of this current but the water movement at these stations also is mostly easterly. South of the equator the currents are westerly, stations 157 to 159 being in the strongest part of the South Equatorial Drift. In the equatorial currents there are irregular vertical water movements. Within the countercurrent there is a strong descending motion and at its borders, i.e., at the inner borders of the North and South Equatorial drifts, there are strong ascending movements, the more pronounced of these being in the North Equatorial Drift. The convection layer is about 50 meters thick from stations 130 to 149 but decreases to less than 10 meters at

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station 151. South of this it increases more or less regularly, reaching 100 meters at station 160.

Section VI (Stations 130 to 125).--This section is in the northeastern Pacific and runs from San Francisco northwestward to a point south of the Gulf of Alaska (latitude 52° north, longitude 151° west). It lies in the eastern end of the North Pacific West Wind Drift and its south-flowing continuation, the California Current; both of which are noticeable to a depth of 400 meters. Stations 129 and 130 are in the region of the coast of California where upwelling occurs above 400 meters. The convection layer is thin, reaching a depth greater than 50 meters only at station 129.

Section VII (Stations 139 to 143).--This is a more or less north and south section in the central North Pacific approximately along the meridian of 160° west and extending from the Hawaiian Islands (latitude 22° north) to about latitude 34° north. In this section the currents are weak, being mostly easterly in the northern part, whereas in the southern part they are westerly. The convection layer is generally about 50 meters thick but varies from 40 meters at station 143 to 70 meters at station 140.

Section VIII (Stations 94 to 104).--This section lies in the tropical western Pacific, running from the Samoan Islands (latitude 13° south, longitude 172° west) north and west to station 104 (latitude 20° 12′ north, longitude 161° 19′ east). This is a section obliquely across the equatorial currents in the western Pacific similar to Section V in the central Pacific. Station 99 is in the center of the eastward-flowing Equatorial Countercurrent which reaches a depth of 300 meters. To the north and south of this the water in the equatorial currents is moving in the opposite direction. As in Section V, there are vertical water movements descending in the countercurrent and ascending at its borders. The convection layer is at least 250 meters thick at the most northwestern station, station 104, but narrows to 100 meters at station 99. At station 96, near the equator, it is greater, approximately 150 meters, whereas south of the equator it is about 50 meters. Thus it will be seen that in the equatorial region this section differs considerably from Section V where the convection layer was extremely thin.

Section IX (Stations 107 to 120).--This section runs from Guam (latitude 14° north, longitude 146° east) north to station 113 near Yokohama (latitude 35° north). From here it continues northeast to station 120 (latitude 47° 02′ north, longitude 166° 20′ east). Stations 107 and 108 in the southern part of the section are within the westerly-moving North Equatorial Drift, but farther north, at stations 109 to 111, there is a weak flow of water eastward. Stations 112 and 113 are in the Kuroshio, a strong current of warm water flowing northward along the east coast of Japan. Stations 114 and 115 are located in the region where the Kuroshio and a south-flowing current of cold water, the Oyashio, meet, thus causing irregular currents. Stations 116 to 120 are in an easterly current of cold water formed partly by the turning eastward of water from the Oyashio and partly by water flowing out from the Bering Sea. Sverdrup states (1931) that the source of the intermediate water of the North Pacific, which circulates clockwise like the water in the troposphere, is near stations 115 and 116, where the two above-mentioned currents converge. The convection layer to the south of station 112 is 40 to 50 meters thick, but to the north of station 112, it is less than 10 meters thick.

Section X (Stations 51 to 52 and 55 to 60).--This section, in the southeastern Pacific, runs southeastward from about latitude 29° south and longitude 115° west, to latitude 40° south and longitude 98° west. In the troposphere the currents run mostly to the southeast. The southern end of the section is in a part of the South Pacific East Drift. The convection layer is thin, exceeding 30 meters only at stations 55, 56, and 57.

Stations 53 and 54.--Stations 53 and 54 are not sufficiently in line with other stations to be included in Section X. They lie to the north of station 56 and east of station 51, south of Easter Island. At stations 53 and 54 the convection layer is thin as at most of the stations in Section X.

Section XI (Stations 93 to 71).--This section runs practically east and west between latitudes 18° and 10° south, from the Samoan Islands (longitude 168° west) to Callao, Peru (longitude 78° west). The stations to the extreme east are in the Peruvian Current and the region of upwelling along the Peruvian coast. The general movement of the water, however, throughout the upper layers of this section is westward. From the coast to longitude 120° west (stations 71 to 80) divergent currents are found to a depth of 100 meters, owing to ascending motion in the region to the southwest of the Galapagos Islands. Below a depth of 200 meters water from the northwest appears to flow toward this region. In the western part of the section between longitudes 120° and 170° west (stations 81 to 93) the currents have a considerable component from the south to a depth of 200 meters. The northward flow of water toward the equator is probably intermittent, thus causing vertical movements that may bring subsurface water to the surface. The convection layer is very thin off the South American coast, mostly less than 20 meters thick. It increases westward, reaching lower than 50 meters at several stations.

Section XII (Stations 45 to 40).--This section lies in the equatorial southeastern Pacific, and extends approximately along the parallel of 2° south from longitude 105° west to the South American coast. The currents are weak and indefinite and the stations are in the area of low temperature which stretches westward from the coast of South America. The convection layer is thin at the coast but increases westward to almost 60 meters deep at the westernmost stations.

Section XIII (Stations 107 to 101).--This section is in the tropical western Pacific. It runs eastward from Guam (latitude 14° north, longitude 146° east) to station 101 at latitude 13° 23′ north, longitude 177° 27′ east, forming a regular curve to the north with station 104 at latitude 20° 12′ north, longitude 161° 19′ east. This curvature toward the north decides the characteristic vertical distribution which appears in the central part of the section. The surface currents in this section are westerly except at station 104 where, in the upper 50 meters, there is probably an easterly movement. The convection layer is at least 50 meters thick at all stations and approaches 100 meters at some stations.

Section XIV (Stations 140 to 130).--This section extends from the Hawaiian Islands to San Francisco. Stations 130 to 134 are included also in Section V, under which they were discussed. Stations southwest of station 134 are in a region of weak and irregular currents flowing

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mostly from the north. From stations 138 to 140 there is a strong surface current toward the west, but this diminishes rapidly below the surface. The convection layer is about 50 meters thick in the northeastern part of the section, but less than 40 meters in the southwestern part.

Section XV (Stations 142 to 146).--This is an east-west section in the central North Pacific between longitudes 161° and 141° west at about latitude 33° north. The currents in this section are somewhat indefinite but are chiefly in an easterly direction with a possible component to the south. The convection layer is less than 40 meters in depth.

Section XVI (Stations 118 to 125).--This section extends in an east-northeasterly direction across the northern part of the North Pacific from station 118 (latitude 42° 29′ north, longitude 155° 24′ east) east of northern Japan to station 125 (latitude 51° 58′ north, longitude 150° 39′ west) south of the Gulf of Alaska, and extends along the Aleutian Islands from stations 122 to 124. The entire section lies in the northern part of the North Pacific West Wind Drift which is well developed to 500 meters. The convection layer is very thin, mostly about 10 meters.

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THE DISTRIBUTION OF PHOSPHATE IN THE SEA

INTRODUCTION

Phosphate and inorganic nitrogen compounds are regarded by many oceanographers as factors regulating and limiting the production of life in the sea. For example, in the North Sea, Atkins (1930 and earlier papers), Harvey (1926, 1928a) and Cooper (1933) found that during the summer either the phosphate or the nitrate content may be reduced to a point at which it cannot be detected by exceedingly sensitive methods. On the other hand, Moberg (1928) reports that the water along the coast of Southern California always contains a sufficient quantity of phosphate to support plant growth although the nitrate may be entirely lacking in the upper 15 meters or more during several months in the summer.

The concentration of both substances in sea water is exceedingly small and varies considerably, not only with the season, but with depth and locality as well. Because of this variability and because of their importance to the life in the sea, the determination of these substances, has been included in most recent oceanographic programs concerned with the study of biological conditions in the sea. This is especially true for phosphate for which this method is more satisfactory than for nitrates.

It is not always practicable to include in the same program the determination of all the plant-nutrient substances that are present in sea water in sufficiently small quantities to be possible limiting factors of the growth of plants. It has been found, however, that as a rule all these substances parallel each other in their distribution. Consequently a reasonably clear picture of the biological fertility of sea water can usually be obtained by determining only one of these substances.

The parallelism in the distribution of various plant nutrients can readily be understood since Redfield (1934) has pointed out that these substances occur dissolved in sea water in the same proportion as in the whole plankton.

VERTICAL DISTRIBUTION

In the illuminated water layers near the surface where adequate light permits an active growth of phytoplankton, the phosphate content is less than at lower levels. The phosphates and other nutrient ions are taken up from the water in the synthesis of plant substances. This drain on the nutrient ions may continue until their concentration becomes so low that they can no longer be utilized and plant activity is curtailed. If small quantities of nutrients are being supplied from greater depths by convective currents, however, or by decomposition of organic material within the photosynthetic zone, a slow growth of plants may occur, regulated by the amount of nutrients available. In this way a vegetable population may act to maintain a continuous depletion of nutrients in the upper water layers. This apparently occurs in certain tropical and subtropical latitudes where the additions of nutrients to the surface layer are small and where other factors controlling the growth of plants, such as light and temperature, are favorable. Thus, at many Carnegie stations the surface water contained 5 mg PO_4 per cubic meter or less. Where the physical factors are not so favorable for plant growth, or where convection or other vertical water movements carry larger quantities of nutrients to the photic zone (as in high latitudes particularly in the winter), the amount of nutrients brought into the upper layers may exceed that utilized by plants and as a consequence there will be an increase in the quantity of phosphate in these layers. At the Carnegie stations south of the Aleutian Islands, surface water containing more than 100 mg PO_4 per cubic meter was found in the summer.

The depth to which photosynthesis takes place varies with the latitude, the season of the year, the turbidity of the water, the density of the plankton population, and probably other factors. In Oslo Fiord, Gaarder and Gran (1927) found that at 10 meters photosynthesis and respiration balanced each other, whereas Marshall and Orr (1927) found this condition at a depth of 20 to 30 meters north of Scotland in the summer. In lower latitudes and farther from the coast suitable conditions for photosynthesis would undoubtedly be found at considerably greater depths. It should be realized, of course, that even at depths where respiration is more rapid than photosynthesis, phosphates and other inorganic substances are consumed by plants. It is possible that all depths at which plants are found in good condition should be included in the photosynthetic zone. According to Steuer (1910) phytoplankton has been found at a depth of 400 meters but it is improbable that active growth occurs at this depth. In most localities it is probable that no great quantities of phosphates are consumed below a depth of 75 to 100 meters. The water, however, may be deficient in phosphate to much greater depths.

The depth to which very low concentrations of phosphate occur is greatly influenced by the depth of the convection layer. Throughout the convection layer the concentration of phosphate is more or less uniform, owing to the thorough mixing of the water. If the lower limit of the convection layer is below the photosynthetic zone, uniformly low concentrations of nutrients will obtain at greater depths than if it is above this zone. Thus, less than 10 mg PO_4 per cubic meter were found at many stations in the North Pacific to depths greater than 200 meters. It is probable that this was not owing to active growth at that depth but rather to the unstable condition of the water in the upper 200 or more meters, which permitted a thorough mixing of the water down to these depths. This allowed the plants nearer the surface to maintain low concentrations of nutrients to depths much below the photosynthetic zone. It is also possible that in areas of sinking, water of low phosphate content may be carried to greater depths than otherwise would be the case.

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Extremely low concentrations of phosphate can occur in the photosynthetic zone or in the convection layer only when there is a marked thermal stratification of the water layers below this zone. Thus, in regions where a layer of water of low phosphate content occurs, there is always a strong density gradient beneath this zone. This prevents any great amount of mixing between the convection zone and the layers below and thus isolates the phosphate of lower levels from the photosynthetic zone. In regions where a strong thermocline does not develop, there is never an extreme reduction of the nutrient salts in the surface layers.

In the layers of water below the photosynthetic zone phosphate is liberated by the decomposition of organic debris and excretory products of holozoic organisms. In our present state of knowledge of the bacteriology of the sea we are unable to state the nature of all the bacteriological processes taking place at various depths but, judging from the vertical distribution of chemical substances in the sea, we are forced to conclude that one series of results of the biological processes occurring in the layers beneath the photosynthetic zone is a liberation of nutrient salts and carbon dioxide and a consumption of oxygen. Thus, the subphotic layers are characterized by high concentrations of phosphate relative to that of the surface layer. In the Pacific the deeper water usually contains more than 250 mg PO_4 per cubic meter.

Assuming there is no horizontal water movement, the quantity of inorganic phosphorus occurring at any given level below the phytosynthetic zone depends on the rate at which it is being produced at that level and on the rate at which it is being transported back to the surface layer where the utilization of phosphate is taking place. Both these factors are influenced by the stability of the water column.

The rate at which decomposition occurs in any layer depends, among other things, on the amount of organic matter available. This, in turn, depends on the abundance of the plankton and on the rate of fall of the organic debris. As the density of the water increases, the rate of fall decreases, and consequently it may be expected that decomposition is more rapid in the thermocline or the stratosphere than in the convection layer. In support of this we find that below the convection layer or photosynthetic zone there is a rapid increase in the quantity of dissolved phosphate with depth.

The rate at which phosphate is returned to the photosynthetic zone will also depend on the stability of the water since dissolved substances can be transported to any important extent only by the water. The process of diffusion of the dissolved substances themselves is too slow to be of any practical significance. There are various forms of vertical water movements. Convection currents are found practically everywhere. They are caused by the settling of small, heavy particles of water that have been cooled by radiation or contact with cold air or have attained a high salinity because of evaporation at the surface, and by the corresponding rising of lighter particles. This type of circulation is probably not effective below the thermocline, but in high latitudes in the winter the density may become uniform throughout all depths so that convective movements may reach from the surface to the bottom.

Another type of vertical circulation is caused by the turbulent character of the movement in horizontal currents. The eddies transport dissolved substances from one layer to another. In the surface layers the eddies in the wind currents are especially effective. The depth to which this effect extends varies with the force of the wind, the latitude, and the density gradient, but only exceptionally reaches below 200 meters. In addition one has to consider the mixing by waves which also takes place near the surface. Vertical components of currents are in some places transporting water from greater depths toward the surface or vice versa. Along the west coast of the Americas and off Africa there is an upwelling of water from intermediate depths (300 to 500 meters) to the surface.

Any type of vertical circulation is effective in renewing the phosphate content of the photosynthetic zone and reducing that of the lower layers so long as it brings water to the surface layer from the subphotic levels.

Thus, we have two opposing phenomena tending to establish the vertical distribution of phosphate in the water column; the liberation of phosphate from sinking organic debris, and transportation of this phosphate to higher levels by vertical circulation. The exact depth at which the greatest amount of phosphate is liberated cannot be stated with any certainty on the basis of present knowledge. One would expect decomposition to be more rapid in warmer water and where the greatest amount of organic material is available, namely, in or immediately below the photosynthetic zone, but at these levels the circulation is stronger than at greater depths and this would tend to prevent the accumulation of phosphate. According to the information obtained by the Carnegie and others, however, it would appear that most of the organic material is decomposed at the lower boundary of, or below, the thermocline.

The Carnegie data show that the maximum concentrations of phosphate and carbon dioxide, as indicated by the pH, and a minimum concentration of oxygen occur at a depth varying from 250 to 1500 meters below the surface, depending on the locality. From this level to the bottom the concentrations of phosphate and carbon dioxide decrease with depth, whereas the concentration of oxygen increases. These facts contradict the statement often found in the literature, namely, that most of the organic material decomposes at the bottom. It is probable that where the water is sufficiently deep practically all this material has been reduced to inorganic substances long before reaching the bottom.

As to whether more decomposition takes place above the level at which the maximum phosphate content and minimum oxygen content are found, it is difficult to say because above this level convective circulation is more effective and it is possible that the accumulation of large quantities of nutrients or a marked reduction in the oxygen content is prevented by interchange of water with the surface layer, where nutrients are consumed by the phytoplankton, and oxygen is dissolved from the atmosphere.

In discussing the distribution of phosphate we have designated as the phosphate transition zone the layer of water below the convection layer, and have defined it as the layer in which the increase in the phosphate content is greater than 0.1 mg PO_4 per cubic meter per meter of depth. In this zone the concentration of phosphate increases from values near those at the surface to as much as 250 to 300 mg per cubic meter at its lower boundary. Since the rate of increase usually becomes less than 0.1 mg PO_4 per cubic meter per meter before the maximum quantity is reached, the layer of maximum phosphate

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content is in most cases below the lower limit of the transition zone, that is, it is found in the stratosphere.

With respect to the relation of the phosphate transition zone to the density gradient, it is interesting to inspect figures C2 to C8, which show the close correlation existing between the phosphate and density gradients at seven Carnegie stations representing various localities of the Atlantic and Pacific oceans.

Figure C2 represents conditions at station 137 (latitude 24° 02′ north, longitude 145° 33′ west). It has been selected as typical of the Pacific for regions in which there is a strong thermal stratification of the water and in which there are no prominent dynamic features. The density curve given in the figure shows a pronounced difference between the lighter water near the surface and the heavy, nearly uniform, water in the stratosphere From the surface to a depth of 200 meters the water is practically depleted of phosphate. In the phosphate transition zone, which extends from 200 to 675 meters, the concentration of phosphate increases to 290 mg PO_4 per cubic meter. At 1000 meters the maximum is attained, with about 300 mg PO_4 per cubic meter. This occurs at about the depth where the rapid increase in the density of the water ceases. At lower levels the phosphate content diminishes more or less regularly, reaching 225 mg per cubic meter at 4000 meters. The phosphate curve shows no modifications attributable to subsurface currents.

When other phosphate curves are referred to the curve for station 137 as a base, the anomalies due to circulation can readily be seen. Figure C3 represents the distribution of phosphate at station 17 (latitude 11° 57′ south, longitude 78° 37′ west), off the coast of Peru in a region of upwelling. Here the upper part of the curve is displaced toward the surface. The density curve shows a similar upward displacement. A high concentration of phosphate, as compared with station 137, occurs at the surface, and the surface layer is limited to the upper 20 meters. The transition zone extends to about 80 meters only. Another interesting feature at this station is the nature of the phosphate gradient between 80 and 900 meters, where the maximum might be expected (as shown by the dashed line), had all the upper 1000 meters of the curve been displaced. It is probable that the peculiar shape of the curve between 80 and 900 meters is owing to the Antarctic Intermediate Current which occurs here. For reasons which will be discussed later, this water may be expected to contain less phosphate than ordinarily occurs as a maximum in this locality. This current also affects the density at these levels, as shown by the curves.

Farther south the effects of the Antarctic Current are still more pronounced. At station 60 in latitude 40° 24′ south, longitude 97° 33′ west, (fig. C4), where there is no upwelling, this current is found between 400 and 1500 meters and its phosphate content is about 50 mg PO_4 per cubic meter less than at station 71. Here again there is a remarkable correspondence between the density and phosphate curves.

Station 130 in latitude 37° 05′ north, longitude 123° 43′ west (fig. C5), is in the region of the upwelling water off the coast of California. Here the distribution of phosphate corresponds to that in the similar region off the coast of Peru except that above 1000 meters the phosphate content shows no definite effect of an intermediate current. The maximum shows the same development as that at station 137 but occurs at 700 meters instead of at 1000 meters.

Figure C6 shows the distribution of phosphate at one of the most northern stations occupied in the Pacific, namely, station 122 at latitude 46° 16′ north, longitude 174° 03′ east. The phosphate curve for this station resembles that at station 137 except that the surface values at station 122 are much higher and the transition zone is considerably nearer the surface than at station 137. The surface value is 130 mg PO_4 per cubic meter and the surface layer is only 20 meters thick. The transition zone extends to only 400 meters. Below this is the usual decrease in phosphate with increasing depth. The high surface values are undoubtedly attributable partly to the inflow of water rich in phosphate from the Bering Sea and partly to the fact that at this latitude the density gradient is considerably reduced during the winter, thus permitting a considerable amount of mixing among the various water strata. It may be noted that even for July, when this station was occupied, the density gradient is not well developed. This, too, may be owing in part to the relatively cold water entering from the Bering Sea.

In the Atlantic, observations to great depths were obtained at a station located at a still higher latitude than station 122. Station 10 (fig. C7) is southeast of Greenland at latitude 50° 19′ north, longitude 34° 15′ west. Although these observations were made in July, both the phosphate and density gradients show the effect of vertical mixing during the previous winter. Below about 100 meters the distribution of phosphate is practically uniform, as is the density, but above this depth the curves show a slight reduction in phosphate as well as in density. The low phosphate content in the Atlantic deep water as compared with that in the Pacific will be discussed later under "Regional distribution," (pp. 16-17).

At station 29 (fig. C8), located in the western trough of the Atlantic at latitude 13° 16′ north, longitude 52° 13′ west, the maximum quantity of phosphate which occurred at about 800 meters is much higher than would be expected from the quantity at lower levels. Since the Antarctic Intermediate Current centers at about 800 meters, it is fairly certain that the water in this current originally had a high phosphate content although the quantity may have been augmented somewhat during its progress toward the north. It is interesting to note that antarctic water, when intruded at this level into the Atlantic, represents a layer of relatively high phosphate content, but when extended into the Pacific, as at stations 70 and 71 (figs. C4 and C3), it represents water low in phosphate relative to the adjacent layers.

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REGIONAL DISTRIBUTION

Carnegie Sections

Section I, stations 24 to 13: more or less north and south from Grand Banks of Newfoundland to latitude 8° north between longitudes 35° and 50° west.--At all stations except the two most northerly stations, 13 and 14, the phosphate content in the surface layer is relatively low. In the central part of the section, where there is a sinking of warm water of high salinity, the line of 10 mg PO_4 per cubic meter is found at a depth of more than 200 meters. In this area the transition zone also is much expanded, the increase in phosphate values with increase in depth being very gradual. The maximum of phosphate occurs at 1000 meters and is represented by less than 125 mg PO_4 per cubic meter. To the north and to the south of this area, much higher values occur in the upper layers. To the north, where the water is colder, values above 150 mg PO_4 per cubic meter were observed. At station 15, where there is a convergence of cold and warm water (see p. 4), the lines of equal phosphate content are bent downward. In the southern part of the section, high values were observed in the Antarctic Intermediate Current, reaching 275 mg at 7000 meters at station 22. In the stratosphere the phosphate content is somewhat more than 125 mg PO_4 per cubic meter in the northern part of the section, but decreases to about 100 mg in the central part, and again increases slightly to the south.

Section II, stations 34 to 25: approximately east and west in the tropical North Atlantic along the parallel of about 12° north from Panama to longitude 37° west.--There is a scarcity of phosphate at the surface throughout the section, water containing less than 10 mg PO_4 per cubic meter extending to 50 and 100 meters at all the stations as shown by the 10-mg line. The transition zone is usually in the upper 500 meters in the western and central parts of the section but rises toward the east and at station 25 it is in the upper 200 meters. The maximum phosphate values occur between 500 and 1000 meters and vary from about 125 mg to more than 275 mg PO_4 per cubic meter. In the eastern part of the section high values are found in the Antarctic Intermediate Current at 700 meters. Two other areas of high phosphate, also due to antarctic water (I-A, pp. 88, 89, 96), occur in the central part of the section. In the stratosphere the phosphate values decrease below the maximum to about 100 mg PO_4 per cubic meter.

Section III, stations 60 to 72, 40 to 37: in the southeastern Pacific, beginning at approximately latitude 40° south, longitude 100° west, extending north-northeast to the coast of Peru at latitude 17° 30′ south, thence northward to the Central American Bight.--Phosphate at the surface is nowhere reduced in this section. The surface values between stations 37 and 40 are from 15 to 25 mg PO_4 per cubic meter. From stations 40 to 71 they range between 25 and 50 mg PO_4 per cubic meter. At station 70 the concentration of phosphate reaches 103 mg PO_4 per cubic meter. South of this it decreases but never reaches 20 mg PO_4 per cubic meter.

In the upper 300 meters the phosphate section shows a marked similarity to the temperature section, the line representing 75 mg PO_4 per cubic meter following the general course of the 15° isotherm. The effect of upwelling, which is shown by the temperature and salinity sections at stations 68 to 70, is quite evident also in the phosphate section where all the lines are raised toward the surface.

The Antarctic Current of low salinity entering from the south at about 400 meters is not apparent in the phosphate section but its effect is easily recognized in the curves showing the vertical distribution of phosphate (I-B, pp. 62-67). From stations 60 to 66 there is a zone of comparatively low phosphate centered at about 400 meters.

The phosphate maximum occurs at about 1800 meters in the south but gradually rises to about 600 meters in the north. The phosphate content is variable, ranging from 225 to 325 mg PO_4 per cubic meter. The Carnegie observations indicate that the bottom water in this region contains between 200 and 250 mg PO_4 per cubic meter.

Stations 35 and 36: in the Central American Bight, east of the north end of Section III.--The phosphate content of the water at these stations is very similar to that at the stations to the west, or to that of the northern part of Section III.

Section IV, stations 51 to 45: in the southeastern Pacific extending approximately north and south from latitudes 29° to 5° south, between longitudes 115° and 105° west.--In the surface layer the concentration of phosphate is everywhere 10 mg PO_4 per cubic meter or more. From south of station 46, however, and centering at station 48, the 25-mg PO_4 line extends to almost 300 meters, indicating relatively low values in the upper levels.

The phosphate transition zone in general follows the thermocline, being found at increasingly low levels toward the south. The tongue of antarctic water from the south, which is shown in the salinity section, is not evident in the phosphate section but is indicated in the station curves of the vertical distribution. The level at which the phosphate maximum occurs, varies between 750 and 1400 meters. The magnitude of the maximum values increases from less than 175 mg at station 50 to more than 225 mg PO_4 per cubic meter north of station 47.

Section X, stations 51 to 52, 55 to 60: in the southeastern Pacific extending southeastward from latitude 29° south, longitude 115° west to latitude 40° south, longitude 98° west.--At the surface the phosphate values show a continuous increase from northwest to southeast. Between stations 51 and 57 there is less than 10 mg PO_4 per cubic meter, whereas in the southeastern part of the section the phosphate content is greater, being 50 mg per cubic meter at station 60.

The layer of maximum phosphate is somewhat indefinite, the concentration continuing to increase below 2000 meters at stations 55, 58, and 59.

Stations 53 and 54: north of Section X, north of station 56, east of station 51, south of Easter Island.--At these two stations the vertical distribution of phosphate is very similar to that at stations 51 and 52 to the west. The surface values vary from 9 to 13 mg PO_4 per cubic meter. The transition zone extends to 500 meters as at station 51 to the west, rather than to 350 meters as at station 56 to the south, indicating that the change in conditions in Section X, which extends from northwest to southeast, from stations 51 to 60, represents a change in a north and south direction rather than in an east and west direction.

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Section XI, stations 93 to 71: practically east and west between latitudes 18° and 10° south, from the Samoan Islands (longitude 168° west) to Callao, Peru (longitude 78° west.--In spite of the fact that this entire section lies in the tropics, there are no extremely low phosphate values. West of station 78 the surface water has a temperature above 25°, yet in that region many surface phosphate values are above 25 mg PO_4 per cubic meter. The highest quantities of phosphate were found toward the east.

The phosphate transition layer follows very closely the isotherms of 15° and 20°, and rises to near the surface toward the coast, where the richest surface water is found. The intermediate layer of antarctic water is not evident in the phosphate section but appears in the station curves of the vertical distribution. The layer of maximum phosphate lies between 600 and 1500 meters with values between 225 and 325 mg PO_4 per cubic meter. The deeper water has a phosphate content of nearly 225 mg per cubic meter.

Section XII, stations 45 to 40: in the equatorial southeastern Pacific, extending approximately along parallel 2° south from longitude 105° west to the South American coast.--This section is another example of an area in the tropics with comparatively large quantities of phosphate at the surface. Although lying very close to the equator, all the surface values were above 25 mg PO_4 per cubic meter. This is in accord, however, with the low temperatures observed here. At stations 42 and 43, where the coldest surface water is encountered, the phosphate values are highest, reaching 52 mg per cubic meter at station 43.

The transition zone lies very close to the surface, above 200 meters in the western part of the section, and in the upper 100 meters in the eastern part. The line of maximum phosphate occurs between 500 and 1200 meters, the quantities at most stations being between 225 and 275 mg PO_4 per cubic meter.

Section V, stations 162 to 148 and 134 to 130: extends northeastward from the Samoan Islands (latitude 14° south, longitude 168° west) to San Francisco (latitude 37° north).--This section demonstrates that the quantity of phosphate at the surface of the sea is not a function of the latitude and that the tropical zone is not necessarily a region of low fertility. It indicates, on the other hand, that the phosphate content of the upper water layers is intimately associated with vertical water movements occurring in the troposphere.

Beginning with station 130 at the northern end of this section, we find 36 mg PO_4 per cubic meter at the surface in a region where there are upwelling of subsurface water, a strong surface current, and relatively low temperatures. As the distance from the California coast increases, the phosphate content of the surface water decreases. Between stations 132 and 150 the phosphate content is extremely low, less than 10 mg per cubic meter, not only at the surface but usually to below 100 meters. Where these low values occur, there are no prominent currents.

Continuing southward we find at station 152, in the North Equatorial Current, 20 mg PO_4 per cubic meter at the surface, but at stations 153 and 154, in the Equatorial Countercurrent, the values are again low. Higher values, about 25 mg PO_4 per cubic meter, are found at stations 155 and 156 which are near the southern border of that current. As previously stated, at the borders of the Equatorial Countercurrent there is probably irregular water movement with vertical components.

The relation of the phosphate content of the sea to the hydrographic conditions is demonstrated by the transition zone in this section. For example, at stations 130 and 131 in the region of upwelling near the California coast, the increase in the phosphate content below the surface layer is extremely rapid, as is also the case from stations 150 to 156 in the North Equatorial Drift and the Equatorial Countercurrent. Southwest of station 132 and northwest of station 150, the transition zone widens until, at station 134, the changes in the phosphate content are the most gradual. Similarly, southwest from station 154 the change in the phosphate content with depth becomes more gradual, although certain irregularities are encountered. The thermocline shows similar variations with the different regions.

The axis of the phosphate maximum lies at about 750 meters from stations 130 to 157, but south of this it gradually descends, reaching 1200 meters at station 162. The maximum phosphate values decrease more or less regularly from 275 mg PO_4 per cubic meter in the northeast to less than 225 mg per cubic meter in the southwest. The deeper water contains approximately 200 mg PO_4 per cubic meter with slightly higher values toward the equator.

Section VII, stations 139 to 143: more or less north and south in the central North Pacific, following approximately meridian 160° west from the Hawaiian Islands (latitude 22° north) to about latitude 34° north.--The line representing 10 mg PO_4 per cubic meter shows a marked deficiency of phosphate in the upper layers, the line reaching to a depth of 300 meters at station 140.

The maximum phosphate content occurs at from 900 to 1600 meters, with over 300 mg PO_4 per cubic meter. Below 3000 meters this concentration is from 225 to 250 mg PO_4 per cubic meter.

Section XIV, stations 140 to 130: from the Hawaiian Islands to San Francisco.--Except at stations 130 and 132 which have already been discussed (Section V), the surface layer is extremely low in phosphate, the 10 mg PO_4 per cubic meter line being found at 100 meters at station 133 and then gradually descending, reaching a depth of almost 300 meters at station 140.

The transition zone usually extends to about 500 meters or more except at stations 130 and 132, where it comes much nearer the surface. The line of maximum phosphate runs for the most part between 500 and 1000 meters, with values between 250 and 325 mg PO_4 per cubic meter. Below a depth of 3000 meters the concentration is approximately 250 mg PO_4 per cubic meter.

Section XV, stations 142 to 146: an east and west section in the central North Pacific, extending approximately along the parallel 33° north between longitude 161° and 141° west.--The surface phosphate values are low, with the 10 mg PO_4 per cubic meter line running at about 100 meters except at station 146, where it is at 200 meters. The maximum values, ranging from 275 to 300 mg PO_4 per cubic meter, are found at 800 meters at the easternmost station to about 1500 meters at the westernmost station. Below the maximum layer there are from 200 to 250 mg PO_4 per cubic meter.

Section VI, stations 130 to 125: in the northeastern Pacific, extending from San Francisco northwestward to a point south of the Gulf of Alaska (latitude 52° north, longitude 151° west).--In this section, which lies north of longitude 37° north, the phosphate at the surface is above 25 mg PO_4 per cubic meter at all stations except

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129. In general, however, the phosphate content in the surface layer increases from southeast to northwest, reaching 125 mg per cubic meter at station 125.

The lines of equal phosphate content bend downward from the two ends of the section, reaching their greatest depth at station 128. The line of maximum phosphate follows the same course, running from 350 meters at station 125, to 1350 meters at station 128, and to 750 meters at station 130. The maximum phosphate content ranges from 250 to 300 mg PO_4 per cubic meter and in the deeper water it is 250 mg per cubic meter or slightly less.

Section VIII, stations 94 to 104: in the tropical western Pacific, extending from the Samoan Islands (latitude 13° south, longitude 172° west) north and west to station 104 (latitude 20° north, longitude 161° east).--From stations 94 to 99 the phosphate values at the surface are about 10 mg per cubic meter, but at the other stations (toward the northwest) they are below this value, the 10 mg PO_4 per cubic meter line running from near the surface at station 100 to about 200 meters at station 104.

The transition zone in this section shows conditions similar to those found in Section V. In the North Equatorial Drift, between 100 and 200 meters, conditions are found at station 100 in this section which are similar to those at station 152 in Section V. The maximum values range from 225 and 275 mg PO_4 per cubic meter and occur at depths of from 700 to 1400 meters except at station 100, where it is at about 2000 meters. In the deeper water the variation in the phosphate content is greater than in most other regions, values between 175 and 275 mg PO_4 per cubic meter occurring.

Section XIII, stations 107 to 101: in the tropical western Pacific, extending eastward from Guam (latitude 14° north, longitude 146° east) to station 101 (latitude 13° 23′ north, longitude 177° 27′ east).--At all the stations the phosphate content of the surface water is very low, the line representing 10 mg per cubic meter running at about 200 meters except at station 107, where it is found at 100 meters.

Relatively far from the surface and from each end of of the section the lines of equal phosphate content curve downward, reaching the lowest depth at station 104. The layer of maximum phosphate is at about 1000 meters except at station 101 where it is at 650 meters. The maximum values range between 225 and 275 mg PO_4 per cubic meter. No observations extend to 3000 meters but at 2500 meters the phosphate is about 225 mg per cubic meter.

Section IX, stations 107 to 120: from Guam (latitude 14° north, longitude 146° east) north to station 113 near Yokohama (latitude 35° north), thence northeast to station 120 (latitude 47° 02′ north, longitude 166° 20′ east). --In this section the hydrographic conditions are complex and the phosphate content at most depths is variable. From the southernmost station, 107, to station 113 the phosphate content in the upper 100 meters or more is less than 10 mg per cubic meter but north of this section the 10 mg per cubic meter line rises to about 100 meters and finally reaches the surface between stations 117 and 118. North of station 117 the phosphate content at the surface rapidly increases to more than 150 mg PO_4 per cubic meter at stations 119 and 120.

In the southern half of the section the most rapid increase in phosphate with depth begins at about 300 meters, but in the northern half it begins immediately at the surface. Between stations 114 and 116 the concentration of phosphate with depth is variable, probably owing to the meeting of water masses of different temperatures.

The axis of the maximum phosphate layer lies between 1000 and 1500 meters in the southern half of the section, but at station 113 it rises, reaching 250 meters at station 120. In most of the section the maximum values vary between 200 and 275 mg PO_4 per cubic meter but are above 275 mg at stations 109, 119, and 120. At greater depths they are between 200 and 250 mg PO_4 per cubic meter.

Section XVI, stations 118 to 125: extends in an east-northeasterly direction across the northern part of the North Pacific from station 118 east of northern Japan (latitude 42° 29′ north, longitude 155° 24′ east) to station 125 south of the Gulf of Alaska (latitude 51° 58′ north, longitude 150° 39′ west), along the Aleutian Islands from stations 122 to 124.--Throughout this section there is no definite surface layer and the phosphate content at the surface is more than 125 mg per cubic meter except at station 118, where it is only 90 mg PO_4 per cubic meter. The center of the maximum phosphate layer is about 500 meters except at station 118, where it is at 1000 meters.

The maximum concentration varies between 250 and 300 mg PO_4 per cubic meter, which is somewhat higher than in other regions. In the deeper water the quantity is about 250 mg PO_4 per cubic meter.

REGIONAL DISTRIBUTION OF PHOSPHATE AT VARIOUS LEVELS

The regional distribution of phosphate is controlled by the same physical and biological factors that control the vertical distribution. It is probable that in the photosynthetic zone plants which consume phosphate are always present except in high latitudes during the winter months. Likewise it is probable that below this zone the proper conditions for the decomposition of organic matter prevail throughout the year and in all localities, resulting in the release of phosphate and other inorganic nutrient substances. Consequently any differences that may exist in the horizontal distribution of these substances must be caused principally by the circulation of the water. Other factors, such as runoff from land and certain biological conditions, should not be lost sight of, but these can be regarded as local or temporary features. Consequently, the circulation of the water, vertical and horizontal, is the principal cause of the general differences in the phosphate content of the water in different regions of the oceans.

In the subsequent discussion the regional variation in phosphate will be taken up for the following levels: (1) at the surface, (2) in the surface layer and transition zone, and (3) at 2000 meters.

Surface

The distribution of phosphate at the surface at all *Carnegie* stations is shown by the chart, figure C9. The relative concentrations of phosphate are indicated by the shading. For regions where the surface water contained less than 10 mg PO_4 per cubic meter this chart also shows the depth to which these low values extended.

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The chart also indicates the months during which the observations were obtained. It will be noted that, except in the tropics where there is little range in temperature, all the investigations in both hemispheres were carried out in the summer.

Atlantic Ocean.--In the Atlantic, north of latitude 36° north, north of station 16, no surface values less than 10 mg PO_4 per cubic meter were observed. Throughout this part of the Atlantic there is an active circulation and the thermal stratification is less pronounced than farther south. It is interesting to note that at station 2 in May the surface water contained 58 mg PO_4 per cubic meter whereas in August of the same year at station 15, which is in the same vicinity, only 11 mg PO_4 per cubic meter were found. This corresponds to the seasonal variation observed by Atkins (1930) in British waters. He found that a concentration of phosphate of about 60 mg PO_4 per cubic meter in the winter was regularly reduced to practically zero by July to September. The low values in summer were attributed to the utilization of phosphate by phytoplankton and to the lack of a renewal from lower levels owing to the stratification of the water during that season.

South of latitude 36° north all the Carnegie stations showed a low phosphate content at the surface and to considerable depths. In the Sargasso Sea, at stations 18 and 19, the water contained less than 10 mg PO_4 per cubic meter to a depth of 225 meters. In the tropics this dearth of phosphate did not extend to quite such great depths, but occurred consistently. The distribution of phosphate observed in the Sargasso Sea may be attributed to the fact that in this area there is sinking of surface water poor in phosphate (see Wüst, 1928). The low phosphate content in the tropics must be attributed to the well-developed thermocline and the absence of any complex currents to disturb the thermal stratification of the water.

Stations 24 to 13, Section I, were occupied by the Carnegie in August and it is interesting to note that Seiwell and Seiwell (1934) report equally low surface values for February and March at six stations in the western North Atlantic and west of Carnegie Section I. At these stations concentrations of less than 10 mg PO_4 per cubic meter were observed to even greater depths than at the Carnegie stations. At their station 1222 (latitude 33° 15′ north, longitude 67° 35′ west), such low values were observed to a depth of 470 meters.

Pacific Ocean.--For the Pacific the distribution of phosphate at the surface has been summarized in a previous paper by Moberg, Seiwell, Graham, and Paul (1930). The distribution is intimately associated with the current systems of that ocean. At all the stations lying north of latitude 40° north, the phosphate content was markedly high, ranging from about 25 to about 150 mg PO_4 per cubic meter with the exception of station 117, east of Japan. Between this station and the next station (118) toward the northeast, there was an extremely abrupt increase in the phosphate content, surface values at stations 117 and 118 being 3 and 90 mg PO_4 per cubic meter respectively. From between these two stations to near the Aleutian Islands there is a southerly flowing current which apparently originates in the Bering Sea. Mixing of water to great depths probably takes place during a considerable part of the year and an abundance of phosphate in the surface water consequently is to be expected. Apparently this phosphate-rich water flows southward until diverted eastward by the North Pacific West Wind Drift (commonly called the Japan Current).

This drift carries the phosphate-rich water eastward and then southward by the California Current, which is formed in the area where the West Wind Drift reaches the Aleutian Islands. The highest phosphate content anywhere obtained at the surface, 142 mg PO_4 per cubic meter, was found at station 119, in latitude 45° 24′ north, longitude 159° 36′ east. From this station the concentration steadily diminishes eastward, to 25 mg per cubic meter at station 129. As regards the high phosphate content in this region, the fact must not be overlooked that in latitudes above 40° north there is considerable convective mixing of the water during the winter months, and this, as has been pointed out previously, will increase the phosphate content in the surface layer. The Carnegie observations were made in July when one would expect that much of the phosphate brought to the surface in this manner would be consumed were there no other source of supply.

Between latitudes 10° and 40° north, with the exception of a few stations near the coast of California, the phosphate content was extremely low, never exceeding 10 mg per cubic meter and often less than half that amount. These low values in this area extended to considerable depths, being found in the upper 100 meters or more at practically all stations with the exception of a few northeast of Japan. The maximum depth to which they extended was 300 meters at station 140.

The small quantities of phosphate observed in the North Pacific between latitudes 10° and 40° north, appear to be associated with two hydrographic features of the region. First, there is a steep density gradient resulting in a minimum amount of mixing of deep water with the surface water. Second, in this part of the Pacific there are no well-developed current systems except near the coasts of California and Japan. It is probable that very little water enters or leaves the area except to a relatively small extent in the two localities mentioned. Thus there appears to be no agency that can materially augment the phosphate content in the surface layer.

The relatively high phosphate values obtained off the coast of California in July and September may be attributed to the upwelling of subsurface water from intermediate depths and possibly also to the transport of phosphate-rich water from the north by the California Current.

Matsudaira (1932) reports the results of phosphate determinations made on surface samples collected by the Japanese training ship, Sintoku Maru, on a cruise from Kobe to San Diego, from San Diego to Hilo, and from Hilo to Kobe, June to September, 1930. Apparently the samples were not analyzed until the vessel's arrival in Japan. The phosphate values obtained are considerably higher than those obtained by the Carnegie in the open Pacific and by the Scripps Institution of Oceanography off San Diego. In these two cases the samples were analyzed soon after collection and it seems necessary to conclude that the values obtained by Matsudaira may be in error owing to prolonged storage of the samples.

South of latitude 10° north, the phosphate content was in general intermediate between that found in the other two parts of the Pacific discussed. In the whole region extending well over the southeastern and tropical Pacific, extremely low concentrations of phosphate occurred at only three stations south of latitude 7° north and these were south of Easter Island. The highest values observed

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in the tropical and South Pacific were off the coast of Peru, where 103 mg PO_4 per cubic meter were obtained at station 70. In this region there is upwelling of subsurface water similar to that off the coast of California and it is possible that the Peruvian Current also brings a supply of nutrients.

Although the surface currents in the southern tropics flow westward from the Peruvian Coast, the source of the phosphate which causes the relatively high values throughout the tropics cannot be attributed to the region off Peru because there is not a continuous decrease in the phosphate content with increased distance from the coast. On the contrary there was a remarkably great variability of the phosphate content at the surface throughout the tropics. The complicated hydrographic conditions in this region probably account for the irregular distribution of phosphate at the surface. For example, Sverdrup (I-A, pp. 102, 106) has shown that the currents in the southern tropics at depths of 100 and 200 meters are irregular and intermittent and that eddies are formed which bring about mixing of water at various depths.

Surface Layer and Transition Zone

Under the discussion of the vertical distribution of phosphate, the phosphate surface and transition zones were defined (see p. 8). The regional variation in the thickness of these zones and in the quantity of phosphate occurring in them is shown in figure C10. In the preparation of this chart the depth of the lower limit of the surface layer was taken as the depth to which the concentration of phosphate was almost uniform. This level was usually very definite as may be seen by reference to the curves of the vertical distribution of phosphate at each Carnegie station. As indicated above, the transition zone was defined as the layer in which the increase in phosphate was greater than 0.1 mg PO_4 per cubic meter per meter of depth but in some instances it was more logical to place its lower limit at a slightly different depth from the one so determined. Where the transition zone was thick the increase in phosphate with depth was less rapid than where the zone was thin, and often represented an increase of less than 0.1 mg PO_4 per cubic meter per meter. The phosphate content for each zone is represented in the chart as the average for all levels within the zone.

Atlantic Ocean.--At the five stations south of Iceland both the surface layer and the transition zone were extremely thin. It is remarkable, however, that at these stations the phosphate content of the transition zone was not so great as that in the Sargasso Sea. The depth of the surface layer varied from 0 to 25 meters; the lower limit of the transition zone varied from 50 to 100 meters. The concentration of phosphate in the surface layer varied from 20 to 34 mg PO_4 per cubic meter; that in the transition zone from 32 to 45 mg PO_4 per cubic meter.

The line of stations from stations 12 to 24 shows the change in conditions from the Grand Banks of Newfoundland, across the eastern edge of the Sargasso Sea, to the North Equatorial Current. These stations are essentially those used in construction of Section I (see p. 10). At the two northern stations conditions resembled those south of Iceland where the zones were thin; the lower limit of the transition zone was above 50 and 100 meters. Southward the zones expanded. The surface layer reached a maximum depth of 350 meters at station 17, whereas the lower limit of the transition zone was mostly well over 500 meters at stations between latitudes 20° and 40° north. South of latitude 20° north the thickness of the zones decreased until at station 24 the surface layer was only 50 meters thick and the lower limit of the transition zone was only 150 meters below the surface. The concentration of phosphate in the surface layer varied from 19 to 27 mg PO_4 per cubic meter at the two northern stations but was below 12 mg PO_4 per cubic meter everywhere to the south. The mean concentration of phosphate in the transition zone was fairly uniform in this series of stations but showed a slight tendency to increase southward. The values varied from 40 to 114 mg PO_4 per cubic meter.

The third series of stations in the Atlantic are those included in Section II, stations 24 to 34 (see p. 10). The depth of the surface layer was rather uniform, varying from 25 to 100 meters. The concentration of phosphate was uniformly less than 10 mg PO_4 per cubic meter. The depth of the transition zone was greatest (625 meters) at station 31 just inside the Caribbean Sea. East and west of this it decreased, particularly to the east where it extended only to 150 meters at station 26. The concentration of phosphate in the transition zone throughout this section was the same or slightly higher than in the southern part of Section I; the values ranged from 48 to 144 mg PO_4 per cubic meter.

The variations in the thickness of the surface layer and transition zones in the Atlantic closely paralleled variations in the thickness of the thermocline. North of station 14 there was a thin layer of warm water, with a sharp density gradient to the underlying cold water. In these regions the increase in phosphate is confined chiefly to this narrow thermocline. Farther south, particularly between latitudes 20° and 40° north, although the surface water was warmer, the warm water extended to greater depths and there was a much more gradual change in temperature and density to the colder water below. Here, too, the increase in phosphate was confined chiefly to the thermocline but since the latter extended over several hundred meters of water, so likewise the phosphate transition zone was very deep. The narrowing of the phosphate zones toward the equatorial regions and their variations in Section II followed similar changes in the density gradients in those regions.

The distribution of phosphate reported by Seiwell and Seiwell (1934) for their three stations west of Carnegie Section I agrees well with Carnegie data, although the transition zone at their station 1169, latitude 16° 22′ north, longitude 41° 10′ west, extends to about 375 meters, which is somewhat lower than that at Carnegie stations in this latitude. At their three stations in the western edge of the Sargasso Sea, however, between latitudes 22° and 34° north, longitudes 65° and 68° west, they show a much more pronounced expansion of both the surface layer and the transition zone than was found by the Carnegie in the eastern edge of that area. In one case their surface layer extended to more than 550 meters. Although their observations extended to 1000 meters, this was not deep enough to show the lower limit of the transition zone in all cases.

Pacific Ocean.--In the Pacific we shall first consider the line of stations between Japan and California, stations 113 to 130, all of which are north of latitude 35° north. At these stations the phosphate content was high in the transition zone as well as in the surface layer. The surface layer was everywhere narrow or entirely

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lacking, especially in the central part of the section which includes the most northern stations occupied in the Pacific. The transition zone was relatively thick except for the stations off the Aleutian Islands, extending only to 175 meters at station 123. It will be noted that where the high surface values were obtained east of station 117 and where the transition zone extended to the surface, the layer of uniform phosphate content was entirely lacking. The mean phosphate values in the transition zone ranged from 104 mg PO_4 per cubic meter at station 115 to 228 mg per cubic meter at station 120. In this region the great quantities of phosphate in the upper layers is the combined result of the partial elimination of the temperature gradient and of the addition of water from the Bering Sea.

South of the above line of stations is the area in which phosphate was almost entirely lacking at the surface. We may consider two lines of stations within this region: (1) the line extending from California to Hawaii, then north and east to station 146, (2) the line starting with station 101 at latitude 13° 23′ north, longitude 177° 27′ east, and extending west and north to Japan. Except near the coast of California all these stations showed a deficiency of phosphate in the surface layer which extended to considerable depths, usually to more than 100 meters and to as much as 200 meters in many places. At these stations also the transition zone was relatively thick, which means that below the surface layer the increase in phosphate with depth was comparatively slow. North of Hawaii at stations 139 to 142, and again in the western Pacific between Guam and Japan at stations 108 to 113, the transition occurred at lower levels than in any other regions investigated, extending to more than 800 meters at all these stations and reaching 1000 meters at stations 142 and 109. The phosphate content of the transition zone at these stations was variable, but nowhere attained the high values observed north of latitude 35° north. It varied from 80 mg PO_4 per cubic meter at station 105 to 188 mg per cubic meter at station 139. From station 134 to the coast of California there was a gradual narrowing of the surface layer and to a slight extent of the transition zone, together with an increase in the phosphate content of both zones. At station 130, where the most pronounced effect of upwelling of subsurface water was shown, the surface layer was only 25 meters thick with a mean phosphate content of 35 mg PO_4 per cubic meter. The transition zone had its lower limit at about 475 meters and contained an average of 207 mg PO_4 per cubic meter.

Proceeding southward we next take up two lines of stations that cross the equatorial currents. The eastern one extends from stations 149 to 161, and the western one from stations 94 to 103. Station 153 in the eastern series of stations, and station 99 in the western series, are in the center of the Equatorial Countercurrent. On either side of this current the North and South Equatorial currents flow in the opposite direction to the countercurrent. The relation of these currents to the distribution of phosphate is more fully discussed on pp. 11 and 12 under the description of sections V and VIII. The noteworthy features of the surface and transition zones in this area are the relative thinness of the layers, particularly in the vicinity of the countercurrent, the absence of extremely low values in the surface layer, and the variability of the concentration of phosphate in both layers.

At station 152, at the northern border of the countercurrent, the lower limit of the phosphate transition zone was at a depth of 175 meters, and that of the surface layer at a depth of only 10 meters. Over the whole area between stations 150 and 155 the entire transition zone was above 300 meters. The average phosphate content of the transition zone in the eastern line of stations varied between 79 and 179 mg PO_4 per cubic meter. In the surface layer the average phosphate content was above 10 mg PO_4 per cubic meter except in the extreme north and reached 60 mg per cubic meter at station 157. Similar but not quite so extreme conditions were found in the western series of stations, with the center of the thin zones at about station 99.

In the absence of disturbances due to horizontal currents, the distribution of phosphate at the stations just discussed would no doubt be quite different from that actually found. These stations lie within the tropics where there is intense insolation of the surface water throughout the year and this normally would be expected to result in thick surface, as well as transition, zones, with consequent reduction of vertical mixing. This would lead to a low concentration of phosphate in the upper layers similar to that found in many of the stations in the North Pacific.

It is evident that in the equatorial regions the effects of the circulation far outweigh the effects of the insolation. According to Sverdrup (I-A, p. 105) there is a strong upward movement of the water along the boundaries of the Equatorial Countercurrent which probably accounts for the proximity to the surface of the transition zone and for the high concentration of phosphate near the surface in the vicinity of the countercurrent. Similar conditions prevail to some degree, however, over the whole equatorial region. The explanation is no doubt to be found in the horizontal water movements, which, according to Sverdrup, produce eddies and possibly other forms of vertical circulation. This may account for the relatively high phosphate values in the surface layer but probably does not contribute to the thinness of the transition zone unless this northward-flowing water has a decided upward component.

The line of stations from Samoa to Peru also lies in the tropics but farther south than the two series just discussed. It includes all the stations presented in Section XI (see p. 11). In general both the surface layer and the transition zone deepen from the coast westward. The lower boundary of the transition zone was 75 meters at station 71 near the Peruvian coast, and 650 meters at station 83 in latitude 17° 00′ south, longitude 129° 45′ west. As was the case in other sections in the tropics, the phosphate content in both layers was variable. The western part of the line lies in the same longitude as the most easterly of the two series of stations crossing the equatorial currents. Here the transition zone extended to somewhat greater depths than in the other two lines of stations just mentioned. This is probably because the more southern stations are in a region of less disturbed hydrographic conditions than prevail farther north. The depth of the surface layer at these stations was the same or greater than that at the more northern tropical stations.

The narrow transition zone in the eastern part of the section is probably caused, in part at least, by the Antarctic Intermediate Current. Nearer the coast the distribution of phosphate is further affected by upwelling and by the Peruvian Current. In the line of stations running from station 60 in latitude 40° 24′ south, longitude

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97° 33′ west, to Callao, Peru, the effects of the upwelling along the coast of Peru are more pronounced. There is also a decrease in the thickness of both the surface layer and transition zone with decreasing distance from the coast. Near the offshore end of the line the surface layer was 100 meters or more in depth at several stations, but near the coast only 25 meters deep. The lower limit of the transition zone was at 375 to 475 meters at the outer stations and was at 75 to 100 meters near the coast. As Callao was approached, there was a considerable increase in the quantity of phosphate ranging from 30 mg PO_4 per cubic meter in the southern part of the line to 106 mg per cubic meter at station 70 near Callao. Similarly, the average phosphate content of the transition zone ranged between 94 and 159 mg PO_4 per cubic meter at the stations remote from land but was above 200 mg per cubic meter along the coast.

The last line of stations on this chart to be discussed extends from station 60, latitude 40° 24′ south, longitude 97° 33′ west, more or less northward and then eastward to near the coast of South America, slightly south of the equator. In this line the phosphate distribution south of Easter Island, stations 60 to 55, resembled that at the same latitudes to the east. From stations 55 to 45, latitude 4° 35′ south, longitude 105° 03′ west, the layers were deeper and their phosphate content less than at the stations to the east. In this part of the series the concentration of phosphate was mostly under 20 mg PO_4 per cubic meter in the surface layer which extended to 200 meters in several places. The transition zone extended to about 500 meters and had an average phosphate content less than 100 mg PO_4 per cubic meter. Station 47, where observations were made in November, in the same vicinity as station 79, latitude 12° 36′ south, longitude 112° 14′ west, was occupied three months later. At the latter station the concentrations of phosphate in both the surface layer and transition zone were considerably greater and the zones somewhat thinner than at station 47. The temperature at the two stations also showed a wide difference. Very little seasonal variation in the hydrographic conditions of the water can be expected at this latitude except as caused by differences in the circulation which, in turn, may be caused by seasonal changes in other localities. At the stations running near the equator from longitude 105° 03′ west to near the coast, remarkably high phosphate values were observed at the surface. At the three stations nearest the coast the transition zone began immediately at the surface. At these stations, as at other stations along the South American coast, the high phosphate content near the surface probably was owing to upwelling of subsurface water and to the Peruvian Current.

The 2000-meter Level

The 2000-meter level was selected for a comparison of the phosphate content of the deep water of the various parts of the oceans. It would have been preferable to use a lower level had sufficient observations been available from below 2000 meters. This level, however, is fairly representative of the deep water as it is well below the transition zone and the tropospheric circulation. Figure C11 shows the scaled values of phosphate in mg PO_4 per cubic meter at 2000 meters for each station at which observations extended to that depth. The mean phosphate values at 2000 meters for certain latitudinal areas in the Atlantic and the Pacific are given in table C1.

Table C1. Comparison of concentrations of phosphate in Pacific and Atlantic at 2000 meters according to *Carnegie* observations

Region	Pacific		Atlantic	
	No. stations	mg/m³ PO_4	No. stations	mg/m³ PO_4
N of 40° N	11	260	7	79
20° - 40° N	25	258	3	111
0° - 20° N	20	240	12	120
0° - 20° S	42	238	....	....
20° - 40° S	19	220	....	....
Mean for all stations	117	242	22	106

Atlantic Ocean.--In the Atlantic the phosphate content of the deep water increased from north to south practically as far as the observations extended. As will be seen from the table, north of latitude 40° north the average value at 2000 meters was 79 mg PO_4 per cubic meter, between 40° and 20° north it was 111 mg, and south of 20° north 120 mg PO_4 per cubic meter. The explanation of this distribution must be sought in the nature of the circulation of the North Atlantic (I-A, pp. 79, 81).

This subject will be discussed further in connection with the discussion of the phosphate content at the 2000-meter level in the Pacific.

Pacific Ocean.--In the Pacific no consistent regional variation in phosphate at 2000 meters is evident from an inspection of the scaled station values. There was a considerable variation from station to station but a progressive change in any direction is difficult to discern. The means for different latitudinal areas (see table C1), however, show a progressive increase from south to north in the concentration of phosphate, the values increasing from 220 mg PO_4 per cubic meter between latitudes 20° and 40° south to 260 mg PO_4 per cubic meter north of latitude 40° north. This south-north phosphate gradient is in accord with the assumption that practically all the deep water of the Pacific originates in the antarctic and not to any important extent at the surface in the warmer areas and that this water is slowly moving northward.

Comparison of Oceans.--The most interesting feature of the phosphate distribution at 2000 meters is the great difference in the values obtained in the Pacific and in the North Atlantic. The mean value for all *Carnegie* Atlantic stations was 106 mg PO_4 per cubic meter, whereas for the Pacific it was 242 mg per cubic meter, or more than twice as high as in the Atlantic. The highest value obtained in the North Atlantic, 166 mg PO_4 per cubic meter, was only slightly above the lowest value, 154 mg, obtained in the Pacific. Thomsen (1931a) also found twice as much phosphate in the Pacific at 2000 meters as in the Atlantic at that depth. Furthermore, he found that the deep water of the Indian Ocean contained approximately the same amount of phosphate as that of the Pacific.

If regions of similar latitude in the North Atlantic and the North Pacific be compared, the difference is equally striking. This is clearly shown in table C1.

At 2000 meters in the eastern North Atlantic, Atkins (1926b) found a phosphate content corresponding to the

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Carnegie results in the central part of that ocean. At a station at latitude 37° 44′ north, longitude 13° 21′ west, he found 104 mg PO_4 per cubic meter, which agrees well with 111 mg per cubic meter as a mean for the Carnegie stations in that general latitude.

According to the phosphate section which Deacon (1933) constructed along the 30th meridian, this deep water of low phosphate content extends southward to about latitude 25° south at 2000 meters and beyond 30° south at 3500 meters. In this section, however, there was a minimum phosphate concentration at about 3000 meters below which there was an increase toward the bottom. Such a feature has not been found anywhere in the Pacific Ocean.

In connection with the difference in the quantities of phosphate in the Atlantic and Pacific it is interesting to compare the concentration of phosphate in the Arctic and and Antarctic oceans. In the Atlantic east of Greenland the oceanic polar front, or region of sinking, extends to latitude 60° north (Meyer, 1928). The Carnegie at station 10, which was in this vicinity, obtained a vertical series of phosphate determinations to a depth of 3000 meters. At this station the phosphate content of the water was almost uniformly 60 mg PO_4 per cubic meter from 500 to 3000 meters (see fig. C7). Similarly, Brujewicz (1931) found in the Barents Sea, which is north of the oceanic polar front, 90 to 105 mg PO_4 per cubic meter at the bottom and considerably less than that amount near the surface. Sverdrup (1933) at nine stations in the Arctic north of Spitzbergen found equally low values. Below 100 meters at all stations the phosphate was rather uniformly distributed with depth. Most of his values were below 97 mg PO_4 per cubic meter and only one was as high as 134 mg per cubic meter.

Kreps and Verjbinskaya (1930, 1932) investigated the seasonal variation in the concentration of nutrients in the Barents Sea. Even in August and September when there was an accumulation of phosphate in the bottom water they never found concentrations exceeding 85 mg PO_4 per cubic meter.

The Antarctic, on the other hand, contains much more phosphate than the Arctic. At fourteen stations in the Weddell Sea, Ruud (1930) found at 450 meters more than 240 mg PO_4 and at most stations about 260 mg PO_4 per cubic meter as compared with less than 60 mg PO_4 per cubic meter in the North Polar Front. Even at the surface Ruud found high values, ranging from 121 to 208 mg PO_4 per cubic meter. Wattenberg (1927a) found similar conditions in the Atlantic at about 50° south. Deacon (1933) reported 187 to 203 mg PO_4 per cubic meter in the deep water of the Antarctic.

Thus, it seems to be well established that the North Atlantic and Arctic oceans have a lower phosphate content than do the other oceans of the world.

According to the distribution of salinity (Meyer, 1928) it is apparent that from the equator to latitude 40° south the water of the South Atlantic between the depths of 2000 and 3000 meters is typically North Atlantic water, originating in the sinking area between latitudes 30° and 40° north. As this water moves southward from the central North Atlantic its phosphate content is gradually augmented by the decomposition of sinking detritus. In the South Atlantic this water is overlain by the Antarctic Intermediate Current which is rich in phosphate and which probably contributes some phosphate from its lower border to the water below. Thus Deacon (1933, p. 233) points out that the maximum amount of phosphate occurs at the boundary between these two currents. He also indicates that "the greatest vertical mixing between the two currents takes place between latitudes 38° and 43° south so that the phosphate is not lost from the antarctic zone but is returned to it in the deep current." In the North Atlantic, on the other hand, there is a slow increase in the concentration of phosphate to great depths, although it always remains relatively low. This distribution of phosphate appears to be peculiar to the North Atlantic. It does not occur in the South Atlantic nor in the Pacific.

The deep water of the North Atlantic is poor in phosphate because practically none of the water from which it originates contains any great quantities of phosphate. The sinking water in the Sargasso Sea contains very little phosphate because of the peculiar hydrographic conditions and because of the phytoplankton at the surface. The North Atlantic Drift consists of warm surface water with a low phosphate content. The Arctic water has been shown by Brujewicz (1931) and Sverdrup (1933) to be relatively poor in phosphate. The cold water in the northernmost part of the Atlantic has a low phosphate content as indicated by the Carnegie observations at station 10. The only source from which the North Atlantic receives water of a phosphate content corresponding to that of the other oceans is the Antarctic Intermediate Current which enters the tropical North Atlantic, but the amount of water contributed by it to the North Atlantic must be regarded as relatively small as compared with the other sources.

The South Atlantic Ocean is rich in phosphate because the main body of water between 2000 and 3000 meters has traveled a comparatively great distance at a level at which phosphate is being liberated, and because the intermediate water above and the bottom water below originate in the Antarctic where the concentration of phosphate is high.

The deep water of the Pacific Ocean is rich in phosphate partly because it does not receive any large quantities of water from other oceans that are poor in phosphate, and partly because it has lacked contact with the convection layer for a long period of time. That the latter is true is indicated by the low oxygen content and the remarkably uniform distribution of salinity and temperature which prevail throughout the deep water of the Pacific.

The greater concentration of phosphate in the Antarctic than in the Arctic can probably be accounted for by the fact that the former ocean is in closer contact with the deep water of the oceans adjacent to it. Sverdrup (1931) has described the probable nature of the mixing of the deep water of the Antarctic with that of the oceans surrounding it. The Arctic, on the other hand, because it is separated from the other oceans by land masses and oceanic ridges, does not receive water from other oceans rich in phosphate. The water which it does receive from the Atlantic and the Pacific must be from relatively near the surface, where the phosphate content is low.

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Table C2. Distribution of phosphate for surface, surface layer, transition zone, and 2000 meters at *Carnegie* stations

Station	PO_4 at surface	Depth of layer 10 mg/m³	Surface layer		Transition zone		PO_4 at 2000 m[a]
			Depth	Mean PO_4	Depth	Mean PO_4	
	mg/m³	m	m	mg/m³	m	mg/m³	mg/m³
1	34	....	....	....	......	....	....
2	58	....	....	....	......	....	....
3	99	....	....	....	......	....	62
4	92	....	....	....	......	....	....
5	16	....	....	....	......	....	61
6	21	....	....	....	......	....	79
7	34	....	25	34	100	45	....
8	13	....	0	....	100	32	....
9	20	....	10	20	50	40	....
10	28	....	10	28	90	37	60
11	27	....	25	27	50	45	68
12	27	....	10	27	100	74	90
13	19	....	20	19	50	40	....
14	11	....	20	11	500	84	134
15	11	....	75	9	825	32	107
16	8	75	200	11	600	59	....
17	9	100	350	11	450	34	....
18	5	225	200	6	700	50	116
19	5	225	200	6	700	42	111
20	5	130	100	5	750	84	130
21	4	120	100	5	300	99	111
22	8	60	50	8	200	114	166
23	4	40	25	5	200	82	99
24	4	50	50	4	150	70	107
25	5	40	25	5	200	106	143
26	5	60	50	5	150	72	....
27	4	80	50	4	200	63	96
28	4	60	75	4	300	48	88
29	3	100	75	3	400	81	103
30	2	100	100	4	500	86	87
31	2	100	90	3	625	144	....
32	2	80	75	2	525	136	....
33	4	90	75	4	475	87	158
34	2	90	75	3	525	110	146
35	15	....	6	15	425	195	193
36	16	....	25	16	350	175	245
37	15	....	30	17	500	192	254
38	20	....	25	20	450	200	268
39	16	....	30	17	500	186	245
40	24	....	0	....	575	198	....
41	32	....	0	....	400	175	....
42	45	....	0	....	275	148	236
43	52	....	30	48	300	94	168
44	38	....	50	35	375	157	235
45	38	....	100	42	550	189	200
46	36	....	100	37	500	175	215
47	17	....	100	19	375	76	207
48	13	....	200	16	475	80	191
49	13	....	200	14	550	90	186
50	13	....	200	14	500	86	158
51	16	....	100	16	500	63	175
52	8	150	100	8	500	69	194
53	13	....	175	13	350	42	190
54	9	5	200	19	400	93	205
55	12	....	100	12	300	41	182
56	9	75	75	9	400	54	154
57	20	....	100	23	375	94	226
58	20	....	75	23	400	93	220
59	38	....	50	38	325	109	248
60	50	....	75	53	375	123	224
61	46	....	0	....	375	111	295
62	32	....	75	32	400	135	252
63	21	....	100	25	400	112	284
64	21	....	100	30	475	108	242
65	24	....	75	26	400	129	260
66	29	....	100	28	300	94	245
67	21	....	100	22	350	129	....

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Table C2. Distribution of phosphate for surface, surface layer, transition zone, and 2000 meters at Carnegie stations--Continued

Station	PO_4 at surface	Depth of layer 10 mg/m³	Surface layer		Transition zone		PO_4 at 2000 m[a]
			Depth	Mean PO_4	Depth	Mean PO_4	
	mg/m³	m	m	mg/m³	m	mg/m³	mg/m³
68	29	....	75	29	300	159	245
69	62	....	25	64	200	211	289
70	103	....	25	108	100	201	276
71	58	....	25	58	75	162	225
72	52	....	25	52	175	156	225
73	44	....	0	....	200	164	232
74	68	....	25	64	175	174	240
75	44	....	75	45	275	171	234
76	50	....	100	46	325	129	236
77	16	...	100	14	275	85	242
78	32	....	100	33	275	110	242
79	34	....	75	34	275	100	310
80	36	....	100	32	375	130	264
81	38	....	100	37	350	78	240
82	34	....	100	34	475	154	249
83	29	....	100	25	650	151	280
84	24	....	150	24	475	104	234
85	40	....	100	41	675	168	284
86	20	....	150	18	650	110	220
87	17	....	200	19	850	152	246
88	16	....	300	16	775	165	240
89	21	....	100	14	675	117	247
90	21	....	100	21	700	142	258
91	21	....	100	23	625	140	288
92	28	....	100	28	475	117	286
93	28	....	100	28	475	107	282
94	14	....	75	14	475	68	190
95	14	....	75	16	375	72	198
96	12	....	75	12	375	79	228
97	24	....	100	23	300	61	228
98	24	....	100	26	400	95	277
99	12	....	75	12	300	107	271
100	10	70	100	11	300	158	268
101	8	170	175	8	525	158	....
102	8	175	175	8	600	124	254
103	5	235	200	6	650	91	....
104	7	200	200	7	700	98	217
105	5	180	150	5	625	80	232
106	5	210	175	6	600	118	239
107	5	90	200	9	475	120	240
108	4	280	200	4	925	137	208
109	3	130	100	4	1000	140	268
110	5	90	75	5	950	118	244
111	5	90	75	5	800	109	241
112	7	130	75	7	800	97	245
113	5	130	50	5	875	118	220
114	7	10	0	....	550	143	234
115	4	30	0	....	675	104	227
116	4	30	10	4	125	109	211
117	3	40	25	4	475	145	255
118	90	....	50	91	375	152	248
119	142	....	0	....	325	231	256
120	137	....	0	....	250	228	266
121	141	....	25	142	225	212	275
122	130	....	25	130	275	194	255
123	113	....	10	114	175	197	....
124	103	....	25	105	200	205	250
125	125	....	0	....	350	219	258
126	76	....	25	76	400	170	275
127	43	....	25	43	500	156	270
128	29	....	50	29	550	147	250
129	25	....	75	26	625	190	269
130	36	....	25	35	475	207	261
131	....	....	....	....	......	....	....
132	15	....	100	15	475	142	251
133	7	135	100	7	625	136	240
134	6	180	175	7	750	178	251

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Table C2. Distribution of phosphate for surface, surface layer, transition zone, and 2000 meters at *Carnegie* stations--Concluded

Station	PO_4 at surface	Depth of layer 10 mg/m^3	Surface layer		Transition zone		PO_4 at 2000 m[a]
			Depth	Mean PO_4	Depth	Mean PO_4	
	mg/m^3	m	m	mg/m^3	m	mg/m^3	mg/m^3
135	7	140	100	5	650	135	263
136	3	170	125	3	675	137	275
137	4	220	200	5	675	165	279
138	5	250	200	4	650	148	274
139	6	200	200	6	650	188	284
140	7	300	275	7	(475)	(176)	....
141	5	100	100	6	950	167	255
142	5	110	100	5	1000	164	301
143	6	90	75	5	875	98	....
144	6	160	175	7	650	105	252
145	6	120	100	6	650	134	286
146	6	200	200	7	750	179	295
147	8	180	175	7	625	182	277
148	....	....	....	....	......	....	....
149	6	210	200	6	575	177	251
150	7	10	100	10	250	130	256
151	....	....	....	....	......	....	....
152	20	....	10	20	175	140	216
153	7	80	75	7	200	123	241
154	7	80	75	7	275	128	227
155	29	....	100	33	275	95	214
156	28	....	125	43	475	171	228
157	47	....	100	60	475	179	250
158	36	....	100	47	650	133	198
159	15	....	75	15	375	79	215
160	12	....	150	15	475	115	219
161	23	....	100	23	475	102	214
162	11	....	100	11	500	87	205

[a] Values scaled from graphs.

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THE DISTRIBUTION OF SILICATE IN THE SEA

INTRODUCTION

The silicate dissolved in the sea is involved in a number of biological and geological processes. Many marine organisms utilize silicate for the construction of their tests or shells, and many bottom sediments contain a high percentage of silica. Of marine organisms, the diatoms are the most important consumers of silicate. To show the dependence of diatoms on dissolved silicon compounds, culture experiments have been conducted by a number of workers; for example, Murray and Irvine (1891), Richter (1906), Allen and Nelson (1910), and Coupin (1922). As regards the form in which these compounds can be utilized, these workers are not in agreement, however, and the question of the nature of the compounds utilized by the diatoms in natural waters is yet to be solved.

HISTORICAL

In the sea a correlation between the abundance of diatoms and the quantity of silicate in the water frequently has been observed. Raben (1905a, 1905b, 1910, 1914) found a seasonal fluctuation in the silicate content of the water of the North Sea and the Baltic corresponding to the seasonal fluctuation in the abundance of phytoplankton. This is strikingly shown in a diagram by Johnstone (1908). Over a period of years Raben found a maximum of silicate in November and February with a minimum in April and May, the minimum following the maximum abundance of diatoms. A similar correlation was later noted by Brandt (1920) in the Baltic.

In the Gulf of Maine, Wells (1922) found concentrations of silicate during the winter nearly ten times higher than in May. In this region maximum diatom growth occurs in March and April. Following this growth silicate increases but is reduced again during the latter part of August, when a second period of diatom growth occurs. During a number of years Atkins (1923b, 1926a, 1928, 1930) has observed a marked seasonal variation in silicate in the English Channel. For example, during 1923 to 1926 a winter maximum of 260 to 310[a] mg SiO_2 per cubic meter fell to 50 and 100 mg in April and June. Thompson and Johnson (1930), in Puget Sound, observed a reduction in the silicate content in May and June; and, in the Strait of Georgia, near the mouth of the Fraser River, Hutchinson, Lucas, and McPhail (1929) noted that the silicate content varied with the growth of diatoms. It was found that the greatest consumption of silicate at depths where diatoms were abundant occurred in August. Conditions here, however, are complicated by the freshwater discharge from the Fraser River. According to investigations carried out at the Scripps Institution, the seasonal variation in silicate along the coast of southern California is less pronounced than in the other localities referred to, probably because of upwelling of subsurface water. Considerable changes in the silicate content at the surface may occur at any time of the year.

Since diatoms can grow only in the photosynthetic zone and since they are the chief consumers of silicate in the sea, we should expect to find a lower concentration of silicate in the upper water layers than in the deeper water. That this is the case has been observed by several workers. Atkins (1926a) presents data for vertical series of samples taken off the south of Ireland, and off Portugal, in the Bay of Biscay, and in the Faroe-Iceland and Faroe-Shetland channels. All these show an increase in the concentration of silicate with depth. The concentrations increased with depth from 120[a] to 190 mg SiO_2 per cubic meter at the surface to about 400 mg per cubic meter at 500 meters. At 1000 meters at the station off Portugal a value of 580 mg SiO_2 per cubic meter was obtained, but at the other stations the concentration at that level was 520 mg SiO_2 per cubic meter or less. At 3000 meters at a station at latitude 30° north, longitude 15° west, the concentration of silicate was 1560 mg SiO_2 per cubic meter. In the English Channel a similar increase of silicate with depth down to 60 meters was observed (Atkins, 1930).

A marked increase in the concentration of silicate with depth was found by Moberg (1926b, 1928) off the coast of southern California and by Bigelow and Leslie (1930) in Monterey Bay. The results of these investigators will be discussed later in a comparison of their data with those of the Carnegie. Hutchinson (1928) studied the silica-diatom relation in the upper 20 to 30 yards in the Strait of Georgia. The decrease in the concentration of silica at the depth where the maximum number of diatoms occurred was very striking. At one station in particular the concentration of silicate decreased from about 4000 mg SiO_2 per cubic meter[b] at the surface to less than 1000 mg SiO_2 per cubic meter at 4 yards below the surface, the depth at which the maximum diatoms were most numerous. Below this the silicate content increased to 2000 mg SiO_2 per cubic meter at 10 and 20 yards. At two other stations a similar correspondence between the abundance of diatoms and silicate and depth was found. In this same locality Hutchinson, Lucas, and McPhail (1929) later determined the silicate content to a depth of 250 yards. The concentration of silicate was 1500 mg SiO_2 per cubic meter at the surface, only 500 mg at 6 yards, and reached a maximum of 2800 mg per cubic meter at 100 yards. Below this there was a slight decrease. Okada (1932) gives the results of the analyses of sixty-eight vertical series of samples taken in the southern part of the Japan Sea by the Syunpu Maru in the summer of 1929. At one station, 37, which is representative of the other stations in that region, the silicate con content at the surface was 187 mg SiO_2 per cubic meter.

[a] To be comparable with Carnegie and other data, Atkins' figures are multiplied by the factor 1.3. See Atkins (1930, p. 848).

[b] On page 301 Hutchinson states his results are expressed in "parts per thousand" but he obviously means "parts per million" as shown by his graphs on the next page where the results are given in mg per liter.

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Between 10 and 50 meters the concentration dropped to 129 and 128 mg per cubic meter, but below this it increased steadily to the lowest depth from which samples were collected. At 1500 meters the silicate content had reached a value of 2450 mg SiO_2 per cubic meter. Subsequently additional investigations of the silicate content in Japanese waters have been reported by Okada in the Journal of Oceanography published by the Imperial Marine Observatory, Kobe, Japan. Previous to the last cruise of the Carnegie the only observations of silicate ever reported for depths over 600 meters was a series obtained by Atkins and Harvey (1925) in the Atlantic. The Carnegie determined silicate at twenty-eight stations and at many of these to depths of 3000 or 4000 meters.

CARNEGIE DATA

The quantities of silicate found by the Carnegie at various localities and depths are shown in four section profiles corresponding to those used for the physical conditions and the other chemical substances (see I-B, pp. 16-55).

Section V, stations 162 to 148, 134 and 133: extends northeastward from the Samoan Islands (latitude 14° south, longitude 168° west) to near San Francisco (latitude 29° north).--Except at stations 133 and 134 the silicate content of the surface water in this section is less than 500 mg SiO_2 per cubic meter. The depth of the 500 mg silicate curve varies considerably, extending to about 300 meters at some of the stations.

The silicate content increases fairly regularly with increasing depth to a level of about 2000 meters. At depths above this level there is a continuous decrease of silicate from northeast to southwest. The curve of 5000 mg SiO_2 per cubic meter, which at station 133 is at about 500 meters, descends rapidly at first and then more gradually and irregularly until at station 162 it is almost at 2000 meters. Below 2000 meters there is a maximum silicate content at stations 133 to 149, 152 to 154, and 161. It is probable that if observations had been obtained from greater depths, a maximum would have been found also at other stations. The maximum value ranges between 6000 and 7000 mg SiO_2 per cubic meter except at the three stations nearest the coast where it is 10,000 mg SiO_2 per cubic meter.

Section VII, stations 139 to 143: more or less north and south in the central North Pacific, following approximately meridian 160° west from the Hawaiian Islands (latitude 22° north) to about latitude 34° north.--The surface water contains less than 500 mg SiO_2 per cubic meter throughout this section. The increase in the silicate content with depth is more rapid than in the case of Section V. The curve of 5000 mg SiO_2 per cubic meter occurs between 500 and 900 meters. A maximum silicate value of 7000 mg per cubic meter was found at station 142, the only station where observations were obtained from sufficient depths to show a maximum.

Section XIV, stations 140 to 133: from the Hawaiian Islands to near San Francisco.--Two of these stations, namely, 133 and 134, are included also in Section V.

The concentration of silicate in the surface layer is over 500 mg SiO_2 per cubic meter, except at stations 137, 138, and 139.

The increase in silicate with depth is similar to that of Section VII, the 5000-mg curve occurring between 500 and 1000 meters. The maximum values at stations 133 and 134 were discussed under Section V. The maximum is found also at station 135 where the highest value is over 9000 mg SiO_2 per cubic meter below 1500 meters. At station 137 there is a maximum of over 8000 mg per cubic meter at 2500 meters. Southwest of station 135 the deepest observations show a silicate content of about 7000 mg SiO_2 per cubic meter.

Section XV, stations 142 to 146: an east and west section in the central North Pacific, extending approximately along the parallel 33° north between longitudes 161° and 141° west.--As at most other stations, the concentration of silicate in the surface layer is below 500 mg SiO_2 per cubic meter. The variation in silicate with depth is similar to that in the other sections in this general region. The curve of 5000 mg SiO_2 per cubic meter lies between 750 and 950 meters except at station 146, where it is at 400 meters. Values above 9000 mg per cubic meter were observed in the deep water at station 144.

VERTICAL DISTRIBUTION

A summary of the Carnegie silicate data is presented in table C3 where the silicate content at standard depths is given for stations north of latitude 20° north and for stations south of that latitude. The mean values for these two groups of stations are also shown graphically in figure C19. As shown by this figure, the concentration of silicate at the surface in the open Pacific averaged about 500 mg SiO_2 per cubic meter at the northern stations and about 300 mg at the southern stations. The curve for the southern stations shows a gradual decrease in silicate from the surface to about 3000 meters where a slight maximum is attained. For the northern stations the curve shows a constant silicate content from the surface to 80 meters, below which there is an increase which is more rapid than in the case of the southern group. At all depths below 350 meters the northern stations average a much higher silicate content than do the southern. This fact will be discussed under "Regional distribution."

The vertical distribution of silicate is controlled by factors similar to those that control the vertical distribution of phosphate and other nutrient substances. As we have pointed out previously, the diatoms, which in most localities and at most seasons are the chief constituents of the phytoplankton, consume silicate in the photosynthetic zone. We have stated also that there is a marked reduction of silicate in the surface layer during active diatom growth and a regeneration of this substance at other periods.

There is a notable difference between the vertical distribution of silicate and other nutrient substances such as phosphate. In the case of silicate the increase with depth below the surface layer is less abrupt and the increase continues to much greater depths than in

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Table C3. Mean silicate content at standard depths in the Pacific (mg SiO_2 per liter)

Depth in meters	Stations 133-149, Between latitudes 20° and 34° N		Stations 150-162, Between latitudes 20° N and 14° S	
	Mean SiO_2	No. of stations	Mean SiO_2	No. of stations
0	0.51	16	0.31	12
5	0.53	16	0.33	12
25	0.51	16	0.40	12
50	0.50	16	0.47	12
75	0.49	16	0.49	12
100	0.60	16	0.62	12
200	0.77	16	0.92	12
300	1.20	16	1.34	12
400	2.01	16	1.56	12
500	3.22	16	1.96	12
600	4.09	16	2.50	12
700	4.63	15	2.96	12
800	5.53	15	3.28	12
900	6.09	15	3.54	12
1000	6.43	15	3.78	12
1500	7.54	14	5.08	12
2000	8.06	13	5.89	11
2500	8.16	10	6.44	8
3000	8.28	6	6.62	5
3500	8.05	6	6.50	3
4000	7.62	6	......	...
4500	7.15	1	......	...

the case of the other nutrients. This is shown graphically in figure C23 where the vertical distribution of silicate and phosphate at station 137 is presented. The continuous increase in silicate to great depths indicates that the silica of the diatom frustules does not dissolve as rapidly as the organic matter of the plankton decomposes. There is also the possibility, however, that organisms having siliceous skeletons sink more rapidly than do others and thus reach greater depths before they are completely dissolved. There are other biological factors which probably contribute to the difference in the vertical distribution between phosphate and silicate. Most of the plankton animals maintain themselves above 500 meters where their excretory products may contribute material quantities of phosphate to the water but probably do not add any appreciable quantities of silicate. This may partly account for the more rapid increase in phosphate than in silicate in the upper 500 meters. Furthermore, the radiolarians are involved in the silica cycle since most of them have siliceous tests. They are found not only in the photosynthetic zone, but at lower levels. Silica removed from the water by these organisms would lower the silicate concentration. Ultimately this silicate would be dissolved, but probably at a lower level. Consequently the radiolarians may be partly responsible for the silicate maximum occurring at lower levels than in the case of the other nutrients

REGIONAL DISTRIBUTION

Figure C19 shows the mean vertical distribution of silicate at two groups of Carnegie stations. Curve A shows the mean distribution at stations between latitudes 20° and 34° north (stations 133 to 149) whereas curve B represents the mean distribution at stations between latitudes 20° north and 14° south (stations 150 to 162). These curves show that the concentration of silicate in the upper 350 meters averaged essentially the same at the two groups of stations. Another similarity is that both curves show maxima at about 3000 meters. There are striking differences, however, between the two groups of stations. At the southern stations the increase in silicate with depth was much more gradual below 300 meters and the quantities were lower than at the more northern stations. At 1000 and 3000 meters the mean values for the two groups of stations were, respectively, 6430 and 8280 mg SiO_2 per cubic meter for the temperate zone, but only 3780 and 6620 mg SiO_2 per cubic meter for the tropics. At all other levels below about 700 meters there was approximately the same difference between the silicate content at the two groups of stations.

It is difficult to assign a reason for this difference in the concentration of silicate in the stratosphere in the two regions of the Pacific. Although there is practically no possibility that the sediments on the bottom of the ocean could affect the chemical composition of the water at great distances from the bottom, nevertheless it is interesting to note that the bottom samples obtained by the Carnegie at the stations in the region where the silicate content was high consist of red clay, whereas those obtained at stations where silicate content was low generally contained a high percentage of calcium carbonate.

Although silicate was not determined in so many localities as was the phosphate, nevertheless the results obtained are sufficient to indicate that the distribution of silicate is determined by the same biological and hydrographic conditions that determine the distribution of phosphate. This indicates that the regional distribution of both is determined by essentially the same physical and biological factors.

At 2000 meters the mean phosphate value for the northern group of stations, between latitudes 20° and 34° north, was 270 mg PO_4 per cubic meter; for stations 149 to 162, south of 20° north, it was 224 mg PO_4 per cubic meter. At this depth the phosphate content at the southern group of stations, therefore, was 17 per cent lower than for the more northern group, whereas in the case of the silicate the difference was 25 per cent.

It is of interest to compare the results obtained by the Carnegie with those from coastal areas of the Pacific. Such a comparison is given in figure C18, where curves are shown for Monterey Bay, the La Jolla region, and the average for sixteen Carnegie stations north of 20° north. In Monterey Bay, Bigelow and Leslie (1930) found the average concentration of silicate for several stations to be 530[a] mg SiO_2 per cubic meter at the surface. The quantity increased rapidly to 50 meters where the mean was 2000 mg SiO_2 per cubic meter. Below this the increase became more gradual and at 600 meters the concentration of silicate was 4350 mg SiO_2 per cubic meter. The two papers by Moberg previously cited present silicate observations at stations off the coast of California to a depth of 150 meters.

[a] The values reported by Bigelow and Leslie have been multiplied by 1.3 to make them comparable with the others. See Bigelow and Leslie (1930, p. 432).

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The curve in figure C18 represents the average of unpublished data for five series of samples taken at a station 10 miles off La Jolla. The curve for this station shows that the concentration of silicate was between 460 and 770 mg SiO_2 per cubic meter from the surface to a depth of 40 meters. Below this it gradually increased, attaining a value of 1320 mg SiO_2 at 100 meters and 3040 mg SiO_2 per cubic meter at 500 meters. The average for the Carnegie stations shows a silicate content between 500 and 800 mg SiO_2 per cubic meter to a depth of more than 200 meters. In fact, the increase in concentration with depth does not become marked until below 300 meters. At 500 meters the average value is approximately the same as for the La Jolla stations but lower than at the Monterey stations. It may be noted that for all three series of stations the quantity of silicate at the surface was approximately the same; at all depths between the surface and 500 meters the Carnegie stations contained considerably less silicate than did the other two series of stations. The differences can probably be explained by the fact that both at Monterey and at La Jolla there is a considerable amount of upwelling of water from intermediate depths where the silicate content is high. Similarly, the higher silicate content of the water at Monterey than at La Jolla can probably be accounted for by the difference in the rate of upwelling in the two localities.

The low concentration of silicate in the upper levels of the open ocean are in accordance with the low phosphate content in the upper water layers in the same region. As explained in discussing the distribution of phosphate, the water in the photosynthetic zone, which has been depleted of nutrients, is carried to depths of several hundred meters by convective currents. As shown in figure C18, the three localities represented in this figure have approximately the same silicate content at 500 and 600 meters. This is to be expected since the upwelling water along the coast comes from above this depth (I-A, pp. 102, 103).

Thoulet (1889) found that distilled water dissolves more silica from rocks than does sea water, whereas Joly (1901) obtained the opposite result. In this connection it is of interest to note that the deep water of the Pacific contains more silicate per unit volume than do many rivers and lakes. Clark (1916) gives an extensive compilation of analyses of natural water from many parts of the world. For many of the rivers and lakes of the world the mean values of silicate are below 8000 mg SiO_2 per cubic meter, a value frequently observed in the Pacific.

From the information available, it seems evident that the Pacific is much richer in silicate than the Atlantic. We have previously pointed out that the concentration of phosphate in the two oceans shows a similar difference (p. 16). Atkins' (1926a) figures for the North Atlantic show a concentration of 160 mg SiO_2 per cubic meter at the surface, 400 mg at 500 meters, 620 mg at 2000 meters, and 1560 mg per cubic meter at 3000 meters. The mean values for these depths for all Carnegie stations at which silicate was determined are, respectively: 420, 2790, 7070, and 7330 mg SiO_2 per cubic meter. Not enough information is available for either the Atlantic or Pacific to permit definite conclusions regarding the difference in the concentration of silicate in the two oceans but the evidence points to a situation similar to that in the case of the distribution of phosphate.

As in the case of phosphate, one would expect to find higher silicate content in the Antarctic than in the Arctic. The maximum silicate values found by Brujewicz (1931) in the Barents Sea were about 1000 mg SiO_2 per cubic meter, indicating that in the Arctic the concentration of silicate is relatively low. Unfortunately, however, there are no observations available regarding the quantity of dissolved silicate in the Antarctic Ocean.

Since silica is required by diatoms for the formation of their frustules, the question has often been raised as to whether the concentration of silicate in sea water is ever sufficiently low to limit the production of diatoms. It is known that the silicate content of sea water can be reduced to much below any of the values found at the Carnegie stations. For example, Atkins (1926a) reports for the North Sea values as low as 40 mg SiO_2 per cubic meter, the lowest concentration that can be determined by the Dienert and Wandenbulcke method. At the Carnegie stations there were very few values below 250 mg SiO_2 per cubic meter whereas the phosphate in a large area of the North Pacific was scarcely measurable by a method that is vastly more sensitive than that used for the determination of silicate. Consequently, it appears highly probable that in the region of the Pacific investigated by the Carnegie, as well as by others previously referred to, silicate does not limit the production of diatoms. It is realized, however, that the concentration to which silicate may be extracted from sea water undoubtedly varies with different species of diatoms and with different physical and chemical conditions of the water.

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THE DISTRIBUTION OF HYDROGEN IONS IN THE SEA

INTRODUCTION

It has long been known that sea water has a slightly alkaline reaction, that is, the concentration of the hydroxl ions slightly exceeds that of the hydrogen ions. The hydrogen-ion concentration, and hence the hydroxl-ion concentration, since the product of the two is a constant, varies in sea water within relatively narrow limits and is regulated by the so-called buffer mechanism or buffer system. This system has been investigated by Buch, Harvey, Wattenberg, and Gripenberg (1932), by Buch (1933), and by Moberg, Greenberg, Revelle and Allen (1934), and it has been shown that the main factors involved are the salts of weak acids, chiefly carbonates and bicarbonates, free and hydrated carbon dioxide, the total salt content, and the temperature. The variations in the hydrogen-ion concentration encountered in the sea are owing chiefly to variations in the total carbon dioxide content, that is, the carbon dioxide existing as free CO_2 or in carbonate or bicarbonate ions. The hydrogen-ion concentration is therefore an approximate measure of the total carbon dioxide in sea water.

The quantity of carbon dioxide is altered by biological activity, being consumed by plants and liberated by animal respiration and decomposition of organic material. For that reason a correlation between the hydrogen-ion concentration and the abundance of plants or animals may be expected. It is also probable that the hydrogen-ion concentration per se may affect the physiological processes of organisms in the sea. Many geochemical processes that take place in the sea are influenced by the hydrogen-ion concentration. Of these a well-known example is the precipitation or solution of calcium carbonate.

An excellent account of investigations of the hydrogen-ion concentration in sea water undertaken prior to 1933 has been published by Wattenberg (1933) and consequently this subject will not be discussed in the present report. Wattenberg also discusses the different factors responsible for variations in the hydrogen-ion concentration in the sea.

As previously stated (p. 3) the data here presented are not corrected for temperature and consequently they are comparable with most of the previously published data except those of Wattenberg. The data are shown in the station graphs (figs. 14-92), in the pH sections I to XVI, and also in table 2 (I-B, pp. 16-55, 56-115, and 183-257).

CARNEGIE SECTIONS

Section I, stations 24 to 13: more or less north and south from Grand Banks of Newfoundland to latitude 8° north between longitudes 35° and 50° west.--At the surface the pH values ranged from slightly above 8.1 at the northern, to more than 8.3 at the southern stations. At some of the stations, mostly in the central part of this section, high pH values extended to considerable depths, the line representing pH = 8.0 being found at depths below 700 meters, whereas at some stations near the two ends of the section it was as near to the surface as 100 meters or less. Except at the last-mentioned stations the change in pH with depth is small. Only at a few stations toward the south is there a marked minimum and at the central stations it is entirely lacking.

At station 19 the pH is uniform below 1000 meters and at station 18 it continues to decrease to 3000 meters. In the northern part of the section pH = 7.9 represents the minimum at 600 meters. In the southern part the minimum occurs in the Antarctic Intermediate Current, the value at station 22 being pH = 7.7. The pH of the deep water throughout the section is approximately 7.9.

Section II, stations 34 to 25: approximately east and west in the tropical North Atlantic along the parallel of about 12° north from Panama to longitude 37° west.--The pH of the surface water is above 8.3 throughout, except at stations 31 to 33 in the Caribbean. The transition zone extends to 500 meters in the western part of the section but toward the east it gradually shifts toward the surface until at station 25 it is confined to the upper 200 meters. A minimum in pH occurs between 500 and 1000 meters, with values between 7.7 and 7.8. The deep water has a pH somewhat over 7.8 in the western part and over 7.9 in the eastern part of the section.

Section III, stations 60 to 72 and 40 to 37: in the southeastern Pacific, beginning at approximately latitude 40° south, longitude 100° west, extending north-northeast to the coast of Peru at latitude 17° 30′ south, thence northward to the Central American Bight.--At the surface there is a general decrease in pH from the tropics to the higher latitudes. At stations 37 and 38 the pH is above 8.3, and at stations 39 and 40 it is between 8.2 and 8.3. From stations 72 to 62 it is between 8.1 and 8.2 except at stations 70 and 63, where it is below 8.1. At the two southernmost stations the values are also between 8.0 and 8.1.

Below the surface there is a more rapid change in pH than at the Atlantic stations, the change being more rapid in the northern part of the section from stations 37 to 68. Here the line representing pH = 7.7 fluctuates between a depth of about 50 and 350 meters, whereas at most stations south of station 61 it is found at depths below 1000 meters. At stations 69 and 70 the lines curve toward the surface which gives evidence of upwelling. A minimum pH value occurs at all the stations at depths ranging down to 1000 meters in the northern part and down to nearly 1600 meters in the southern part of the section. The minimum pH values at nearly all the stations are between 7.6 and 7.7. In the deeper water the pH is slightly more than 7.7.

Stations 35 and 36: in the Central American Bight, east of the north end of Section III.--The pH concentration at these stations is similar to that in the northern

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part of Section III. The surface values are 8.31 and 8.23 respectively. At other depths the pH corresponds to that at stations 37 and 38 in Section III.

Section IV, stations 51 to 45: in the southeastern Pacific extending approximately north and south from latitudes 29° to 5° south between longitudes 115° and 105° west.--In this section the surface pH values are lower at the stations nearest the equator than at the stations farther south. Similarly, the change in pH with depth is much more abrupt at the northern than at the southern stations. The minimum pH, between 7.6 and 7.7, occurs near 500 meters at the three northern stations and at 1000 to 1800 meters at the other stations in the section, at most of which the pH is slightly over 7.7.

Section X, stations 51 and 52, and 55 to 60: in the southeastern Pacific, extending southeastward from latitude 29° south, longitude 115° west, to latitude 40° south, longitude 98° west.--In this section there is a gradual decrease in the surface pH from above 8.2 at the northwesternmost stations to less than 8.1 at the southeasternmost stations.

The transition zone and the level at which the minimum pH values occur, as well as the pH values in the latter and in the deeper water, resemble those of the southern part of sections III and IV.

Stations 53 and 54: north of Section X, north of station 56, east of station 51, south of Easter Island.--The distribution of pH at these stations corresponds to that at the stations to the east (Section X) rather than that at the stations to the south. The surface pH is 8.22, the same as at station 51, and the variation with depth follows closely that at this station.

Section XI, stations 93 to 71: practically east and west between latitudes 18° and 10° south, from the Samoan Islands (longitude 168° west) to Callao, Peru (longitude 78° west).--At the surface the pH increases from east to west as do the temperatures. The lowest pH value (8.13) in this section is found at station 71 near Callao. Toward the west the values increase to more than 8.3 at the stations in the western part of the section.

The level of the greatest change in pH with depth is in the upper 100 or 200 meters near the coast but gradually deepens toward the west until its lower limit is found at about 500 meters. The minimum values are below pH = 7.7 and are found between 500 and 1000 meters in the eastern part of the section, but in the western part they are above 7.7 and occur at depths between about 1000 and 2000 meters. Similarly, in the deep water east of station 85 (longitude 136° west) pH is slightly over 7.7, and west of this station it is above 7.8.

Section XII, stations 45 to 40: in the equatorial southeastern Pacific, extending approximately along parallel 2° south from longitude 105° west to the South American coast.--At the surface the pH values range from slightly under 8.1 to slightly over 8.2 at station 40. The vertical pH gradient is fairly steep with the minimum where the pH values are below 7.7, occurring at depths between 500 and 700 meters. In the deep water the pH is below 7.7 to the west and somewhat above that in the eastern part of the section.

Section V, stations 162 to 148 and 134 to 132: extends northeastward from the Samoan Islands (latitude 14° south, longitude 168° west) to San Francisco (latitude 37° north).--At the surface the pH values at all the stations are comparatively high being over 8.3 at most of the stations and even over 8.4 at a few stations. At a few meters below the surface, pH values above 8.4 occur at several stations.

Except at the center of the section the change in pH with depth is fairly gradual. At station 152 the gradient is exceedingly steep, as is the case with temperature and phosphate and the other substances determined, the bottom of the transition zone being at about 100 meters. From this station toward the northeast and southwest there is a gradual change toward conditions prevailing at the majority of the stations.

Minimum pH values occur at the depths ranging from 500 to 1000 meters from the first stations off the California coast to slightly beyond the equator, but farther south they are found near 1500 meters.

The minimum pH values range from between 7.6 and 7.7 at several stations in the central part of the section to between 7.7 and 7.8 at the stations near each end of the section. In the deep water, below 2000 meters, the pH is usually about 7.8.

Section VII, stations 139 to 143: more or less north and south in the central North Pacific, following approximately meridian 160° west from the Hawaiian Islands (latitude 22° north) to about latitude 34° north.--At the surface the pH values vary from 8.3 to 8.4, the former value being found to a depth of about 250 meters at station 140. At this station, however, the change in pH below this depth is the most rapid. In general the zone of rapid change in pH extends from 500 to 1800 meters, the minimum values being found between 700 and 1000 meters with pH ranging around 7.6. Below the minimum, as in the case of the other sections, pH increases with depth, reaching 7.8 at about 3000 meters.

Section XIV, stations 140 to 130: from the Hawaiian Islands to San Francisco.--Stations 132 to 134 were discussed under Section V, and stations 139 to 140 under Section VII.

At the other stations the surface water has a pH between 8.3 and 8.4. The change in pH with depth is fairly gradual and resembles that at most of the two adjoining sections mentioned. The minimum values occur between 500 and 1000 meters with values ranging from about 7.7 at station 138 to near 7.8 at station 132. In the deeper water the pH varies from 7.8 to 7.9.

Section XV, stations 142 to 146: an east and west section in the central North Pacific, extends approximately along the parallel 33° north between longitudes 161° and 141° west.--This section resembles Section VII, which includes also stations 142 and 143, and most of Section XIV.

At the surface the pH is over 8.3, the change with depth being fairly gradual and the minimum occurring between 500 and 1000 meters. The minimum values are somewhat lower than at most of the stations in this region, being below 7.6, and in the deeper water the pH is also somewhat lower than at other stations.

Section VI, stations 130 to 125: in the northeastern Pacific, extending from San Francisco northwestward to a point south of the Gulf of Alaska (latitude 52° north, longitude 151° west).--At the surface the pH is relatively low, being about 8.1 at all the stations. At the three stations nearest the American coast, 127 to 129, the transition zone extends to about 500 meters, but northwest of this it gradually rises and at the last station of the section it is confined to the upper 150 meters.

The depth of the minimum layer shows a similar change, being at 800 meters at stations 127 to 129 and at about 400 meters at the last station of the section. The

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minimum values vary between 7.5 and 7.6. Below the layer of minimum pH the values increase, reaching about 7.7 near 3000 meters, the greatest depth investigated.

Section VIII, stations 94 to 104: in the tropical western Pacific, extending from the Samoan Islands (latitude 13° south, longitude 172° west) north and west to station 104 (latitude 20° north, longitude 161° east).--The pH of the surface water is between 8.2 and 8.3 except at stations 97 and 98 where it is less than 8.2. Water with nearly the same pH as at the surface extends to a depth of 100 to 200 meters. At station 100 the transition zone is concentrated between the 100- and 200-meter levels and the pH gradient is steep, as is the case with the phosphate gradient. At the other stations the change in pH with depth is more gradual, extending to more than 500 meters at some stations farthest north.

There is no pronounced minimum pH value although at most stations slightly lower values were found at about 1000 meters than elsewhere. Below 2000 meters pH values are about 7.7.

Section XIII, stations 107 to 101: in the tropical western Pacific, extending eastward from Guam (latitude 14° north, longitude 146° east) to station 101 (latitude 13°23′ north, longitude 177° 27′ east).--At the surface the pH is well above 8.2 at all the stations, these values extending to a depth of about 100 meters except at the two southernmost stations where they reach nearly 200 meters.

The transition zone extends to about 600 or 700 meters at the stations near the center of the section, except at station 101 where it extends to about 400 meters only.

At stations 101 and 102 a minimum is practically lacking, but at the other stations it is shown at a depth of about 1000 meters with pH values between 7.6 and 7.7.

Below 2000 and 3000 meters the pH is between 7.7 and 7.8.

Section IX, stations 107 to 120: from Guam (latitude 14° north, longitude 146° east) north to station 113 near Yokohama (latitude 35° north), thence northeast to station 120 (latitude 47° 02′ north, longitude 166° 20′ east). --In this section the pH varies more from station to station than in the other sections. The pH at the surface fluctuates from less than 8.2 to nearly 8.3 except at the two most northern stations where it is below 8.0.

The change in pH with depth is fairly gradual in the southern part of the section, stations 107 to 115, the transition zone extending from 500 to 1800 meters. At the other stations the change is more abrupt, the lower limit of the transition zone being at about 200 meters at stations 119 and 120.

The depth of the minimum pH layer, which at most stations is well marked, varies in a similar manner; ranging from 1500 meters at station 112 to 350 meters at station 120. The minimum values are between pH 7.5 and 7.7, the lower values being found in the north. Below 3000 meters the pH is above 7.7.

Section XVI, stations 118 to 125: extends in an east-northeasterly direction across the northern part of the North Pacific from station 118 east of northern Japan (latitude 42° 29′ north, longitude 155° 24′ east) to station 125 south of the Gulf of Alaska (latitude 51° 58′ north, longitude 150° 39′ west), extending along the Aleutian Islands from stations 122 to 124.--Stations 118 to 120 were discussed under Section IX with which they are included.

The distribution of pH in this section resembles that of stations 119 and 120. The surface water has a pH below 8.0 at stations 121 and 122 but is slightly higher at the other stations. There is no layer of uniform pH at the surface, the values usually being higher at 5 meters than at the surface and then decreasing rapidly with depth. The depth of the lower limit of the transition zone is at 300 meters at station 122, at slightly more than 100 meters at station 124, and at intermediate depths at the other stations.

There is no distinct layer of minimum pH, the lowest value (between 7.5 and 7.6) being found at the lower limit of the transition zone. From this level pH increases, the values between 2000 and 3000 meters being about 7.7.

VERTICAL DISTRIBUTION

It has already been pointed out that as in the case of other plant nutrients biological activities affect the quantity of carbon dioxide, and consequently the pH, in the ocean. In the photosynthetic zone more carbon dioxide is ordinarily utilized by the plants than is liberated by respiration or decomposition of organic material. Similarly, carbon dioxide is liberated by animal respiration and organic decomposition in the water strata below the photosynthetic zone from where it may be carried by the water to the upper levels where it again becomes available for plant growth. The carbon dioxide cycle in the sea differs from that of the other nutrients in that carbon dioxide may be given off to the atmosphere or absorbed from it. As to whether carbon dioxide is given off from or absorbed by the water depends on the carbon dioxide tension or pressure and this in turn depends on a number of factors, the chief of which are the carbon dioxide content of the water and the temperature. In the Atlantic, south of latitude 20° north, Wattenberg (1933) in most localities found the carbon dioxide tension of the sea to be about the same as that of the atmosphere, except along the coast of Africa where it was higher in the sea water.

For one hundred and fifty-nine Carnegie stations in widely separated regions the average surface pH value is 8.22. In order to determine whether or not this value represents equilibrium in the carbon dioxide tension between the sea and the atmosphere, it would be necessary to know the titratable base content and to consider the temperature. According to Buch (1933) a pH of 8.22, at a temperature of 30° and a salinity of 34 per mille, represents a carbon dioxide tension in equilibrium with the atmosphere. For a temperature of 20°, which would probably be near the average for the Carnegie surface observations, this equilibrium is represented by a pH of 8.20.

The vertical distribution of pH in the surface or convection layer at the Carnegie stations was rather variable. In some cases the pH was constant throughout the entire layer whereas in others it increased, decreased below the surface, or varied in an irregular manner. Similar irregularities were found in the distribution of oxygen and undoubtedly were owing to biological activities. It will be remembered that gases do not readily diffuse through the water and any irregularities in their

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concentration brought about by organism can be removed, within a reasonable length of time, only by water movements.

In the transition zone the pH decreased rapidly with depth and then more slowly until at most stations a minimum, ranging from 7.5 to 7.9, was reached at a depth which varied from 200 to 1500 meters. At some stations the minimum was lacking, pH remaining practically constant from below the transition zone to the greatest depth at which values were obtained.

Below the depth of minimum value, at the stations where it occurred, the pH increased slowly with increasing depth. At no station was there conclusive evidence of a decrease in pH near the bottom as was sometimes found by Wattenberg (1927b, 1933). At 3000 meters the pH varied from 7.7 to 7.9 and at 4000 meters usually from 7.8 to 7.9.

The variation in pH with depth can be correlated with biological activity and with the circulation of the water. Remembering that pH varies inversely as the carbon dioxide content, the high pH at the surface can be accounted for by the fact that the carbon dioxide tension of the water is nearly in equilibrium with that of the atmosphere, either because part of the carbon dioxide has escaped from the water or has been consumed by the plants, and the low values in the deeper water are owing to the excess of carbon dioxide produced by animal respiration or decomposition of organic material. The increase in pH below the depth at which minimum values were found indicates that decomposition or animal respiration reaches a maximum at an intermediate depth. Such a conclusion is corroborated also by the distribution of phosphate and of oxygen.

The striking correlation between the vertical distribution of phosphate and of pH is shown in figures C12 and C13. Figure C12 represents a region (station 137) of relatively undisturbed hydrographic conditions, whereas figure C13 (station 71) represents a region where the circulation is more active. In the latter region, off the coast of Peru, upwelling of subsurface water occurs, causing an upward displacement of both the phosphate and pH curves in the upper 500 meters. Further, it is of interest to note that at station 71 both the pH and phosphate curves show the effect of the Intermediate Antarctic Current, the pH values in the water of this current being lower and the phosphate values higher than would probably be the case if this current were lacking.

REGIONAL DISTRIBUTION

Surface.--Since the solubility of carbon dioxide in sea water increases with decreasing temperature, one would expect the carbon dioxide content of the surface water to be greater, and, therefore, the pH to be lower, in the higher latitudes than in the lower. In general, the *Carnegie* found this to be the case but evidently the explanation is not to be found in the variation in the solubility of carbon dioxide but rather in the nature of the circulation of the water.

In the Atlantic the pH values at the surface north of latitude 40° north were between 7.9 and 8.2 (see fig. C14), whereas south of this latitude they ranged between 8.2 and 8.4. In the Pacific the observations in the tropics and intermediate latitudes usually gave values between 8.2 and 8.4. At the most northerly station, about latitude 50° north, the pH of the surface water was about 8.0, whereas at the most southerly stations, in latitude 40° south, it was about 8.1. These variations are too great to be owing to differences in the solubility of carbon dioxide. According to Buch (1933), sea water of average salinity and with the same carbon dioxide tension as the atmosphere has a pH of 8.14 at a temperature of 0° and a pH of 8.22 at 30°--a difference of only 0.08 for a temperature range greater than that encountered by the *Carnegie*. On the other hand, the variation in pH with depth has a much greater magnitude than that directly attributable to variation in temperature, and the differences in pH found by the *Carnegie* at the surface were undoubtedly caused by differences in vertical water movements. This assumption is further strengthened by the fact that in the Atlantic Wattenberg (1933) found the lowest pH values at the equator near the coast of Africa and from there low values extended well out to the center of the Atlantic. Along the coast of Africa upwelling of subsurface water occurs, and this unquestionably accounts for the low pH values found there.

That the pH at the surface of the sea is not primarily a function of the temperature of the water is further indicated by the strong negative correlation between *Carnegie* values of pH and phosphate content which, of course, is not affected by temperature. This relation is shown graphically in figure C16. For these two variables the coefficient of correlation was calculated to be 0.621, with a probable error of 0.032. With the temperature, the pH showed a positive correlation of about the same magnitude but apparently the temperature variations found cannot entirely be accounted for by differences in latitude, notably in regions where abnormally low temperatures occurred, as, for example, off the coasts of California and South America and near the Aleutian Islands. In these regions the presence of surface water in the convection layer was undoubtedly partly responsible for the relatively low temperature as well as for the high phosphate content and the low pH. It may therefore be concluded that, in general, the differences in the pH of sea water caused by the solubility of carbon dioxide are masked by the differences caused by vertical circulation and biological activity.

Subsurface.--Below the surface layer, also, there is a close correlation between pH and phosphate, not only vertically but horizontally. The variations in pH at various depths along the entire course covered by the *Carnegie* are represented graphically in pH sections I to XVI (I-B, pp. 56-115) and are described on pages 25 to 27.

The variation in pH at the surface has already been discussed. As would be expected, at the depths falling within the transition zone, the variability in pH was the greatest, depending on the thickness of this zone and on the nature of the vertical gradient. At greater depths the pH, like the phosphate content, varied slightly from station to station, although these variations gave no definite indication of regional differences either in the Atlantic or in the Pacific. There was a significant difference, however, between the pH of the deep water of the Pacific and the deep water of the North Atlantic. At 2000 meters in the Atlantic (see fig. C15) the pH was about 7.9, whereas in the Pacific it usually ranged between 7.7 and 7.8. At 4000 meters a few observations

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are available from each ocean and at this depth in the Atlantic the pH was about the same as at 2000 meters, namely, 7.9, but in the Pacific it was between 7.8 and 7.9.

Palitzsch (1912), at a station west of Portugal, found the water at 2000 meters to have a pH of 7.95. Atkins (1925) later determined the pH at 2000 meters in practically the same locality and found it to be 7.94. The Carnegie observations in the same latitude, but farther west, agree well with these results (see table 2, stations 3 and 5; I-B, pp. 183-257). Between the equator and latitude 20° north in the Atlantic, Wattenberg (1927b) found that at 2000 meters the pH, not corrected for temperature, generally ranged between 7.8 and 7.9.

As stated on page 16, the Carnegie data show the phosphate content of the deep water of the Pacific to be greater than that of the North Atlantic. No doubt the explanation given for this difference applies, in general, also in the case of pH. In discussing the phosphate content as observed by the Carnegie, it was pointed out that a large part of the water that goes to make up the deep water of the North Atlantic is derived from the surface in the central part of the North Atlantic where the phosphate content is low. In this area the pH is high. In the region centered about Carnegie station 18 in latitude 29° 47′ north, longitude 40° 36′ west, a depression of the lines of equal pH was found. This accords with the theory that in this area the surface water is sinking.

The comparative amounts of phosphate in the Arctic and the Antarctic were also discussed and, according to the available information, the Antarctic has the higher phosphate content. There appears to be a similar difference between the Arctic and the Antarctic with respect to the pH. Brujewicz (1931) in his extensive investigations of the Barents Sea rarely found pH values below 8.0 at any depth. For the Antarctic Ocean the only data available are those obtained by Ruud (1930). His observations extended only to a depth of 450 meters, except in one case when they extended to 900 meters. At 450 meters he usually found the pH to be about 7.8 and the one observation at 900 meters showed a pH of 7.77. It appears, then, that the pH in the Antarctic is considerably lower than that in the Arctic and comparable with that found in the Pacific.

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THE DISTRIBUTION OF OXYGEN IN THE PACIFIC OCEAN

INTRODUCTION

Prior to the last cruise of the Carnegie very little information was available regarding the distribution of oxygen in the deep water of the Pacific. The Challenger expedition (Dittmar, 1884) made about twenty-five determinations of oxygen on subsurface water from various parts of the Pacific but, because the samples were taken in varying depths, and only one at each station, the data are inadequate for any conclusions regarding the distribution of oxygen. On board the Planet, Brennecke (1909) determined oxygen at several stations between New Guinea and Hong Kong, but the information he obtained is not complete even for this limited area because practically no samples were taken below 1000 meters and even above this depth the number was insufficient. Schmidt (1925) reported the oxygen content of the water down to a depth of 1000 meters at a station occupied by the Dana in the Gulf of Panama. Off the coast of southern California the oxygen content had been determined by the Scripps Institution of Oceanography and in Monterey Bay by Bigelow and Leslie (1930). In neither case were observations taken below 1000 meters and at that time it was not known whether the conditions in the coastal areas were representative of the conditions in the open Pacific. The Carnegie data give a fairly complete picture of the distribution of oxygen in the tropical and eastern North Pacific. Some of these data already have been published (Moberg, 1930; Moberg and Graham, 1930).

Since the Carnegie cruise (1928-1929) there have been a number of investigations of the oxygen content in the Pacific but additional information is still needed, particularly from the South Pacific. From data obtained by the Dana in 1928 to 1929, Thomsen (1931b) constructed a profile showing the distribution of oxygen in various depths between Panama and New Caledonia. Ito (1930) investigated the oxygen content of the water between New New Guinea and Japan. Thompson, Thomas, and Barnes (1934) report the results of oxygen determinations made by the University of Washington at a number of stations in the Gulf of Alaska and near the Aleutian Islands. In 1933 R. H. Fleming, of the Scripps Institution of Oceanography, made a thorough survey of the oxygen conditions in the Gulf of Panama and along the Pacific coasts of Panama and Costa Rica, on board the U. S. S. Hannibal. R. R. Revelle, also of the Scripps Institution of Oceanography, determined oxygen at five stations off the coast of southern California on board the U. S. Coast and Geodetic steamer Pioneer in 1933, and at eighteen stations between the Aleutian Islands and the Hawaiian Islands on board the U. S. S. Bushnell in 1934. Some of the data obtained by Fleming and Revelle are presented in the present report.

The Carnegie obtained vertical series of determinations of oxygen at all stations occupied during the cruise from San Francisco to Samoa, stations 130 to 162, and at two stations in the North Atlantic and four in the southeastern Pacific. The data for stations 130 to 162 have been used in the construction of four section diagrams, showing the concentration of oxygen in milliliters per liter, and four diagrams showing the concentration of oxygen in percentage of saturation. R. R. Revelle of the Scripps Institution of Oceanography very generously supplied the authors with the oxygen data which he obtained on board the U. S. S. Bushnell in August 1934. From these data a section showing the distribution of oxygen between the Aleutian Islands and Hawaii (fig. C17), in milliliters per liter, has been constructed. In addition to the Carnegie and Bushnell data, the authors have had access to the unpublished oxygen data obtained by Revelle on the U. S. Coast and Geodetic steamer Pioneer off the California coast and by Fleming on the U. S. S. Hannibal in the Gulf of Panama and off the coast of Central America in 1933. For the use of these data the authors wish to express their gratitude.

VERTICAL DISTRIBUTION

The quantity of dissolved oxygen in sea water is controlled by a number of physical, chemical, and biological factors. At the surface of the sea the oxygen content of the water is approximately in equilibrium with that of the atmosphere and, since the solubility of oxygen varies with the temperature, and to a much lesser extent with the salinity, its quantity ranges from about 4.5 ml per liter in the tropics to about 8 ml per liter in the polar regions. In the photosynthetic zone, that is, in the upper 50 or 100 meters or at even greater depths in some localities, oxygen is liberated by plants during photosynthesis, and when photosynthesis takes place rapidly in water not in contact with the atmosphere the concentration of oxygen may rise considerably above the saturation point. Since plants ordinarily are most abundant some distance below the surface, the highest concentrations of oxygen are usually encountered at some level in the upper 100 meters. At all depths oxygen is consumed by plants and animals during respiration and by the decomposition of organic material.

To account for the distribution of oxygen in a body of water it is necessary to consider also the circulation of the water. Since the sea derives its oxygen only at or near the surface, from the atmosphere or from photosynthetic organisms, and since oxygen diffuses through the water exceedingly slowly, the deep water depends entirely on water movements for its supply of oxygen.

Although different localities exhibit marked differences in the vertical distribution of oxygen, it is possible to recognize a general type of distribution which is common to all areas in the Pacific investigated by the Carnegie and to distinguish the following four layers of water which differ from each other with respect to the oxygen content.

1. A narrow surface layer in which the oxygen content is approximately in equilibrium with the atmosphere and nearly uniform. In this layer the quantity of oxygen is determined largely by the oxygen-retaining capacity of the water, hence chiefly by the temperature.

2. A layer in which the oxygen content is higher

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than at the surface or at any other depth, owing to the fact that oxygen is liberated by photosynthetic organisms more rapidly than it is consumed, and mixing is not sufficiently rapid entirely to prevent the accumulation of excess quantities of oxygen. At some stations this maximum oxygen layer was not found.

3. A transition zone in which the oxygen content decreases to a minimum. This decrease is no doubt owing to a reduction of the amount of oxygen transferred by vertical mixing and to the consumption of oxygen by animals and by oxidizing chemical substances.

4. A deep layer in which the oxygen content increases slowly with depth but never attains the same concentration as at the surface. The water in this layer receives no oxygen from the water strata or from the atmosphere directly above, and contains only the oxygen it had when descending from the surface, less the amount consumed by respiration and oxidation.

The decrease in the oxygen content in the transition zone and the minimum oxygen values at the lower limit are owing partly to a reduction in the amount of convective water movements and partly to the consumption of oxygen by animals and decomposing organic material. The relation to the circulation is indicated by the fact that the oxygen minimum always occurs below the thermocline. It is safe to assume, therefore, that the water below the thermocline receives no appreciable quantities of water from higher levels and consequently that its oxygen supply cannot be replenished from the atmosphere.

The increase in the quantity of dissolved oxygen below the minimum is probably owing to the fact that animals and organic matter become increasingly scarce with increasing depth. However, if there were no oxygen supplied to the stratosphere, even small quantities of decomposing organic matter continuously supplied would eventually result in an absolute absence of oxygen at the level of the minimum oxygen content and this layer without oxygen would gradually extend more deeply until it reached the bottom. The water in the stratosphere, however, is continuously, although slowly, being replaced by water from the surface and this water, of course, is approximately saturated with oxygen. This subject will again be discussed under "Regional distribution" of oxygen.

That the vertical distribution of oxygen in the sea is closely correlated with the distribution of other substances involved in biological activities, such as hydrogen ions and phosphates, is demonstrated in figure C20 which represents the distribution of these three substances at Carnegie station 137 which is representative of the North Pacific. In the upper 200 meters where the pH was high and the phosphate content low, the quantity of dissolved oxygen was high. At the surface the oxygen content was 4.64 ml per liter and at 50 meters over 5 ml per liter. In the transition zone where the phosphate content increased and the pH decreased with depth, the dissolved oxygen content decreased rapidly. A minimum oxygen content of 0.54 ml per liter or only 8 per cent of total saturation occurred at about 700 meters, the same depth at which the minimum pH values were found and approximately at the same depth as for the phosphate maximum. Below the oxygen minimum there was a slow increase in quantity of oxygen with depth, concurrent with an increase in pH and a decrease in the phosphate content. The deepest observation, at 4343 meters, gave 3.46 ml per liter of oxygen which is seven times as much as the minimum quantity found at 700 meters and about three-fourths the quantity of the surface water. An examination of the graphs for the stations at which oxygen was determined reveals that the correlation between oxygen, phosphate, and pH found at station 137 is the usual condition.

Of particular interest is the distribution of these substances at station 152 in the North Equatorial Drift where the vertical distribution differed from that at most other stations because of unusual hydrographic conditions. The curves for this station are shown in figure C21. It will be noted that there was a marked increase in the phosphate and a corresponding decrease in pH and oxygen content in the upper 200 meters. The extensive layer of low oxygen content at this station will be discussed later.

Section V, stations 162 to 148 and 134 to 132: extends northeastward from the Samoan Islands (latitude 14° south, longitude 168° west) to San Francisco (latitude 37° north).--The oxygen content at the surface from stations 130 to 132 is above 5.0 ml O_2 per liter. South of station 133 it drops to between 4.0 and 5.0 ml per liter. This can be expected from the higher temperature of the water. South of station 158 it is usually below 4.0 ml per liter. In the upper 100 meters at most stations in this section, there is a layer of water of which the oxygen content is higher than either above or below. At stations 130 and 131 the maximum oxygen content is 6.0 to 7.0 ml per liter. South of station 151 it is between 4.0 and 5.0 ml per liter. In percentage saturation this appears as an almost continuous layer between stations 130 and 151, with over 100 per cent saturation. South of this the maximum is between 90 and 100 per cent saturation.

The oxygen transition zone at depths above 500 meters exhibits the same general features as the phosphate transition. Below the transition zone there is a very definite minimum of oxygen throughout the whole section. This minimum changes in depth and in magnitude from north to south. At the northernmost station, 130, it is represented by 0.1 to 0.3 ml per liter or less than 5 per cent of saturation. This condition exists to south of station 133 where the absolute concentration of oxygen is not quite so low but the percentage saturation does not rise until past station 134. At station 150 the minimum again drops below 0.3 ml per liter or 5 per cent saturation. At this station the minimum is divided by a layer of higher oxygen content, one branch of the minimum occurring at 300 meters and the other at 500 meters. At station 151, latitude 15° north, the minimum is represented by a thick layer lying between the levels of 100 and 450 meters, in which the oxygen content was only 0.05 ml per liter. This value lies so close to the experimental error of the determination that it is possible that in this layer there is no dissolved oxygen at all. As one continues southward, two minima are again seen at station 152 at about 100 and 400 meters, respectively. The station curves of the vertical distribution of oxygen (I-B, pp. 56-115) show that these minima persist to station 154, south of which they converge at 500 meters with a value increased to more than 0.5 ml per liter. This minimum continues southward at about 400 meters, rising somewhat at station 157 where it again sends off a branch with values below 0.5 ml per liter at 500 meters. It becomes less extreme southward with oxygen values steadily increasing to more than 2.0 ml per liter at station 162. A layer of high oxygen content can be seen between the two minima coming in from the south at station 161 at about 700 meters, where the oxygen content is more than 3 ml per liter. Northward it rises

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to higher levels and decreases in value but is still very evident at station 157 at 400 meters. There will be a general discussion of the oxygen minimum later (p. 34).

The oxygen content of sea water can often be taken as an index to dynamic conditions, but there are instances when it cannot be so used. For example, the intermediate antarctic water of low salinity penetrating to station 151 at 100 meters cannot be seen in the oxygen section because of the proximity of this water to the surface. The oxygen maximum at about 150 meters at stations 159 and 160, however, may be caused in part by the inflow of water from the south. Such a flow is evidenced also in the salinity distribution. Similarly, the maximum at station 161 at 700 meters may be associated with the influx of water of low salinity at this point.

Below the depths at which the minimum occurs, the oxygen content increases more or less regularly with depth. Although the oxygen content is somewhat variable at great depths, it definitely increases from north to south at the 2000- and 3000-meter levels. The observations indicate that the bottom water has an oxygen content between 3.0 and 3.5 ml per liter or about 40 per cent of saturation. One observation made near 4000-meter depth at station 152 shows 3.63 ml per liter.

Section VII, stations 139 to 143: more or less north and south in the central North Pacific, following approximately meridian 160° west from the Hawaiian Islands (latitude 22° north) to about latitude 34° north.--The oxygen content at the surface throughout this section is above 5.0 ml per liter. A maximum is found with its center at a level of about 100 meters at the north end and 75 meters at the south end of the section. This maximum has a value between 5.0 and 6.0 ml per liter or over 100 per cent of saturation. At station 143 more than 6.0 ml per liter occurs, which represents an oxygen saturation greater than 110 per cent. Below this maximum there is a clearly defined secondary minimum. The level of this is indicated by the broken line on the chart at about 250 meters. It is more clearly shown in the vertical distribution curves than in the section. It will be recalled that a double minimum was found at the southern stations in Section V.

The primary minimum occurs at 1000 meters at station 143. From here southward it rises to 800 meters and increases in value. In the north it is represented by less than 0.5 ml per liter (less than 5 per cent saturation); south of station 141 it is between 0.5 and 1.0 ml per liter (10 to 20 per cent saturation). Below this minimum the oxygen increases regularly. The only observations made below 3000 meters were at station 142 where it is indicated that the bottom water contains more than 3.0 ml per liter of oxygen or is more than 40 per cent saturated.

Section XIV, stations 140 to 130: from the Hawaiian Islands to San Francisco.--Stations 130 to 134 already have been discussed under Section V. South of station 134 the surface oxygen values vary between 4.0 and 5.0 ml per liter. The maximum at 100 meters at station 134 is continued west to station 140 with values generally above 5.0 ml per liter or more than 100 per cent saturation. The secondary minimum which was seen in sections V and VII, to the south and west of this section, occurs here from station 140 eastward to station 137, (latitude 24° 02′ north, longitude 145° 33′ west), although it is apparent in the vertical oxygen section only at station 139 at 225 meters.

The marked minimum at 1000 meters at station 135 continues westward at a slightly lower depth and the oxygen content increases slowly to above 0.5 ml per liter or 10 per cent saturation. In the deep water there is a definite increase in quantity of oxygen from northeast to southwest. In this region the bottom water probably contains from 3.0 to 3.5 ml of oxygen per liter. The highest value observed was 3.46 ml per liter at 4340 meters at station 137.

Section XV, stations 142 to 146: an east and west section in the central North Pacific, extending approximately along the parallel 33° north between longitudes 161° and 141° west.--The surface oxygen content is above 5.0 ml per liter, which represents 90 to 100 per cent saturation. The layer of maximum oxygen values lies at about 100 meters with water of more than 5.0 ml per liter of oxygen, corresponding to more than 100 per cent saturation.

At about 250 meters there is a secondary minimum, as represented on the oxygen section by a broken line. To see this minimum more clearly, reference should be made to the station curves (I-B, pp. 56-115). The concentration of oxygen in this minimum layer is less than 5.0 ml per liter. This minimum was observed in sections V, VII, and XIV at all stations west of longitude 145° west and south of latitude 16° north. Reference to the vertical curves shows that it is only faintly evident at station 146 (latitude 31° 51′ north, longitude 140° 50′ west). It is not seen in the curve for station 145 because no observations were made at the level at which it would be expected to occur.

The primary minimum is encountered at 1000 meters with values below 0.5 ml per liter or about 5 per cent of saturation. Below the minimum layer the oxygen content increases, reaching 3.0 ml per liter, or more than 40 per cent saturation, at 3500 meters.

BUSHNELL SECTION

Hawaiian Islands to Aleutian Islands: latitude 50° 30′ north, longitude 175° 16′ west to latitude 25° 33′ north, longitude 159° 38′ west.--The Bushnell section is constructed from data furnished by R. R. Revelle from sixteen stations (Ba to Bp) occupied by the U. S. S. Bushnell on a line between the Aleutian Islands, latitude 50° 30′ north, longitude 175° 16′ west, to Hawaii, latitude 25° 33′ north, longitude 159° 38′ west. It is extended to the south by one Carnegie station (140) and to the north by a station (5055-17220) investigated jointly by the Hydrographic Office of the U. S. Navy and the Oceanographic Laboratories of the University of Washington (see Thompson, Thomas, and Barnes, 1934). The position of the latter station is latitude 50° 55′ north, longitude 177° 20′ west. For comparison Carnegie stations 142 and 141 are also shown in the section between Bushnell stations Bk and Bl, and Bm and Bn, respectively. The Bushnell stations were occupied between August 18 and 26, 1934; the University of Washington station on June 10, 1933; and the Carnegie stations between October 3 and 7, 1929.

This section in its northern part cuts across the North Pacific West Wind Drift (sometimes called the Japan Current) and continues southward through the center of the North Pacific vortex. The currents in the

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southern part of the section are weak and in a westerly direction. The University of Washington station is probably in the narrow westerly current close to the Aleutian Islands. The convection layer is 40 meters thick at station Ba. At most of the other stations of the section it is rather uniformly about 20 meters thick but widens toward the south to 95 meters at station Bo, and narrows to 75 meters at station Bp.

The oxygen content of the surface water in the northern part of the section is over 6 ml per liter; at station Bf it drops to below 6 ml per liter, and from station Bk to the south end of the section it is between 4 and 5 ml per liter. This decrease in the oxygen content of the surface water from north to south is to be expected because of the increasing temperatures and the decreasing solubility of oxygen.

As regards the subsurface distribution of oxygen in this section there is a close resemblance to the distribution in the regions investigated by the Carnegie in the northeastern Pacific (see sections VII, XIV, and XV). There is a layer of maximum oxygen content throughout the section in the upper 100 meters at all stations except at the extreme south where it drops to 150 meters. In the colder water to the north this layer contains more than 7 ml per liter of oxygen but southward it decreases to less than 6 ml per liter.

The transition zone is nearest the surface at the northernmost Bushnell stations where its lower limit is above 300 meters. At the station (5055-17220) to the north it extends to 425 meters. Proceeding southward, the transition zone sinks and expands, reaching its lowest depth and maximum expansion at station Bi, latitude 36° 52′ north, where it extends from 500 to 900 meters. South of this station it contracts somewhat and rises. At Carnegie station 140 it lies between 440 and 650 meters.

Throughout the section there is a well-developed layer of minimum oxygen content. Although the level of the axis of this minimum falls and rises from north to south in a manner paralleling that of the transition zone, the thickness of the layer poor in oxygen decreases continuously from the northernmost Bushnell station (Ba) southward. At station Ba there is a layer of water 1210 meters thick, from 280 to 1490 meters below the surface, in which the oxygen content is less than 1 ml per liter. At station Bh, where the layer that is poor in oxygen reached its greatest depth below the surface, its thickness was 1080 meters, extending from 820 to 1900 meters below the surface. South of this station this layer rises and narrows more rapidly. At Carnegie station 140 the layer with less than 1 ml per liter of oxygen is only 400 meters thick, lying between 650 and 1050 meters below the surface. Water extremely deficient in oxygen, represented by concentrations less than 0.5 ml per liter, occurred in two parts of the section--toward the north at stations Ba and Bb, and toward the south between stations Bh and Bo.

Below the layer of minimum oxygen there is a fairly regular increase in the oxygen content with depth at all stations. At 3500 meters there is somewhat more than 3 ml per liter of oxygen. In the deep water there is a considerable decrease in the oxygen content from the south northward to station Bh, latitude 39° 51′ north, but from here northward there is an increase, although the concentrations in the northern part of the section are never as great as those in the extreme southern part. Thus, at the 2000-meter level the oxygen content, which at Carnegie station 140 is 2.25 ml per liter, decreases to 1.15 at station Bh, and then increases northward to 1.65 ml per liter at station Ba, and 1.55 at station 5055-17220. Similar conditions were found at the 300-meter level.

HANNIBAL AND PIONEER SECTIONS

The oxygen data obtained by R. H. Fleming on board the U.S.S. Hannibal in the Gulf of Panama and off the coasts of Panama and Costa Rica in 1933 are in excellent agreement with the data obtained by Schmidt (1925) in the Gulf of Panama. In connection with the regional distribution of oxygen it is of importance to note that the deep water at the Hannibal stations contained more oxygen than did the Carnegie stations farther north.

At the five stations occupied by the Pioneer, Revelle found the distribution of oxygen to be very similar to that found by the Carnegie at station 130 which was occupied four years earlier and several hundred miles farther north.

REGIONAL DISTRIBUTION

Surface Layer

Revelle's data, obtained on board the U.S.S. Bushnell, show that north of latitude 40° north at the surface the water was supersaturated with oxygen. Farther south the relative concentration of oxygen at the surface was somewhat less. At most stations between latitudes 40° and 20° north the oxygen content of the surface water was just under saturation, the relative concentration varying from 96 to 101 per cent of saturation at all stations except station Bk, where it was 90 per cent. At the next group of stations, between the equator and latitude 20° north, the quantity of oxygen at the surface was still less. At the five stations farthest south, latitudes 6° to 13° south, the relative concentration of oxygen ranged from 78 to 89 per cent of saturation. There is thus a decrease in the dissolved oxygen content at the surface from north to south, not only in the absolute quantity, which is to be expected because of the temperature increase, but also in the percentage of saturation. This probably reflects a variation in the amount of phytoplankton from north to south, except at the southernmost group of stations where the unusually low oxygen content indicates that the water at the surface had been mixed with subsurface water of a normally low oxygen content. This is further indicated by the fact that at these stations the phosphate content at the surface was relatively high.

In at least part of the convection zone, the oxygen content was the same as at the surface. At stations north of latitude 20° north surface values extended to a depth varying from 10 to 15 meters, but seldom to more than 5 meters at stations farther south. The position of

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the layer of maximum oxygen content varied in a similar manner, usually being found at some 30 to 90 meters at the northern stations but at much higher levels at the other stations. This maximum was observed at practically every station but it was more pronounced at the northern stations. North of latitude 20° north the maximum oxygen values represented saturation at all but three stations, whereas south of this latitude there was only one station where supersaturation was observed. This decrease from north to south in the maximum oxygen values parallels the concentration of oxygen found at the surface.

Transition Zone and Oxygen Minimum

The lower limit of the transition zone was characterized by a minimum of oxygen and there was usually a more or less uniform decrease in the oxygen content from the lower limit of the surface layer to this minimum. The oxygen transition zone did not coincide with the temperature transition zone for the minimum oxygen layer always occurred below the thermocline. If the boundary between the troposphere and stratosphere be defined by the 10° isotherm, as Sverdrup suggests (I-A, p. 83), following Wüst (1929), then the oxygen minimum layer was usually a feature of the stratosphere but in some instances of the troposphere.

In the transition zone the distribution of oxygen was more variable, both vertically and horizontally, than in any of the other zones. The lower limit of this zone, that is, the depth of the minimum oxygen values, occurred at from 650 to 1495 meters in latitudes north of 20° north but much nearer the surface in the tropics and especially in the North Equatorial Drift and the Equatorial Countercurrent. These differences can be correlated with similar differences in the thermal stratification of the water but in some cases there is evidence that horizontal water movements also played a part. A condition such as existed at station 144 (see station graphs, I-B, pp. 110-111), where there was a marked increase in the oxygen content between 300 and 400 meters, strongly indicates the presence of a narrow layer of water recently descended from near the surface. This layer was observed at most of the Carnegie stations north of latitude 20° north but it was best developed, hence of most recent origin, in the area between longitudes 150° and 160° west. In the Bushnell stations this layer can be detected only as far as station Bm, latitude 30° 20′ north, but at the stations farther north there were similar layers of relatively high oxygen content at higher levels.

The minimum oxygen values increased gradually from about 0.2 ml per liter at the most northerly stations to about 0.8 ml per liter near latitude 20° north. Between this latitude and 6° north the quantities were 0.3 ml per liter or less. At station 151 where conditions were more extreme than at the other stations, the oxygen content decreased from over 5 ml per liter at 25 meters to less than 0.1 ml per liter at 100 meters. Between 100 meters and 400 meters there was a layer of water in which there was practically no oxygen, the amount observed ranging from 0.03 to 0.06 ml per liter or from 0.5 to 1 per cent of saturation. At 500 meters the quantity was only slightly higher, or 0.15 ml per liter.

The low concentration or almost complete absence of oxygen at most levels above 500 meters at the stations in the North Equatorial Drift and the Equatorial Countercurrent is very striking but must be considered merely as an accentuation of a condition found at all the other oxygen stations in the North Pacific. This accentuation is owing to the peculiar hydrographic conditions of the region (see I-A, pp. 105, 106). At stations 151 and 152 there was a strong stratification of the water above 100 meters as shown by the temperature and density profiles, and consequently no appreciable quantities of water rich in oxygen could sink from the surface layer. A similar stratification occurred above 200 meters at nearby stations. Sverdrup points out that there was a strong upward movement at the borders of the Equatorial Countercurrent, particularly at the northern border, that is, at stations 151 and 152. The effects of this upward movement are quite evident in all the above profiles. It must be realized that the rising water comes from a level at which the oxygen content is already very low. As it moves into this region and rises, it is subjected to a further depletion of its oxygen while ascending through the depths at which the oxygen consumption is most rapid.

The oxygen profile for Section V shows that at the southern stations there were two oxygen minima, separated from each other by a layer of water of fairly high oxygen content occurring at about 700 meters at station 161 and rising to 400 meters at station 157. The salinity profile for the section shows two layers of water coming in from the south, the Intermediate Antarctic Current with low salinity at 700 meters, and another layer of water with high salinity, probably recently descended from the surface, coming in at about 200 meters. The water of both these currents would be expected to be well supplied with oxygen and it is probable that they, at least in part, account for the higher oxygen values in the transition zone and the less extreme minimum at the southern stations.

Stratosphere

In the water below the transition zone the oxygen content was found to increase slowly with increasing depth. This increase is summarized in table C4, which shows the average quantities of oxygen at several depths in four zones of the Pacific for which data are presented in this report. Only stations at which samples were taken to a depth of at least 3000 meters are included in this table.

Table C4. Summary of oxygen content in deep water of the Pacific Ocean

Latitudes	No. stations	Oxygen in ml per liter			
		2000 m	2500 m	3000 m	3500 m
° °					
50 N - 40 N	4	1.4	2.0	2.6	.....
40 N - 20 N	17	1.7	2.2	2.7	.....
20 N - 0	5	2.1	2.3	2.6	2.95
0 - 13 S	3	2.8	3.1	3.1	3.4

The water in the stratosphere receives practically no oxygen from the troposphere but since it is certain that the water in the stratosphere originally descended from the surface, it is safe to conclude that its oxygen content was originally fairly high, that is, at least 4.5 ml

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per liter. Even at great depths some oxygen is consumed by organisms and decomposing chemical substances, and table C4 shows that in the stratosphere a considerable amount of the oxygen had been consumed. The highest value obtained in the North Pacific, at 3500 meters, was only 3.25 ml per liter.

Table C4 also shows that the oxygen content increases from south to north. This indicates that, since at these depths the oxygen is not replenished by vertical water movements, the water at the most southerly stations has descended from the surface more recently than at the stations farther north. This means that in the central and eastern Pacific the water in the stratosphere is moving in a northerly direction. That the oxygen content increases toward the south is further corroborated by the data published by Thomsen (1931b) who shows that at all the stations occupied by the Dana south of the Carnegie stations, the oxygen content in the deep water was considerably higher than that found at the southernmost Carnegie stations.

Only two of the Carnegie oxygen series in the southeastern Pacific extend to great depths. At both station 52 (latitude 31° 28′ south, longitude 112° 51′ west) and station 57 (latitude 33° 59′ south, longitude 106° 43′ west) the oxygen content at 2000 meters was about 3.5 ml per liter. This value is higher than those obtained farther north in the central Pacific and further corroborates the conclusion that the origin of the deep water lies to the south.

COMPARISON OF OXYGEN CONTENT OF THE ATLANTIC AND PACIFIC OCEANS

The distribution of oxygen in the Atlantic is much better known than it is in the Pacific. In the Atlantic oxygen has been investigated, among others, by the following: Gaarder (1927), in the eastern basin of the North Atlantic; Seiwell (1934), in the western basin of the North Atlantic; Wattenberg (1929), in the Atlantic south of latitude 20° north: and Deacon (1933), in the western basin of the South Atlantic.

In comparing the data published by the above investigators with those obtained in the Pacific, a striking difference in the oxygen content of the deep water of the two oceans is apparent. This difference can be illustrated by the data from two stations, one occupied by the Deutschland (Brennecke, 1921) in the Atlantic at latitude 27° 46′ north, longitude 27° 36′ west, and the other by the Carnegie (station 137) in the Pacific at latitude 24° 02′ north, longitude 145° 33′ west. The oxygen content at these two stations is shown in figure C22.

At the Deutschland station the water below 2000 meters contained between 5 and 6 ml of oxygen per liter of water and similar, or even greater quantities, were obtained at seventy-five other stations investigated by the Deutschland in the North and South Atlantic. At the Carnegie station in the Pacific at this depth the oxygen content was less than 3 ml per liter. Wattenberg (1929) also found that below 2000 meters in the Atlantic the concentration of oxygen was greater than 5 ml per liter. According to his summary the oxygen content in the Atlantic at all latitudes greater than 20° north or south is practically the same as at the Deutschland station represented in figure C22. In the tropics, however, the minimum oxygen values were lower and in the eastern part of the Atlantic sometimes fell below 0.5 ml per liter but even here the oxygen content below 2000 meters was between 5 and 6 ml per liter. The Carnegie obtained two oxygen series in the Atlantic. One, at station 3, latitude 44° 00′ north, longitude 36° 10′ west, shows very good agreement with that of the Atlantis station 1157 in the same locality (Seiwell, 1934) except that slightly high values were obtained in the deep water. The Atlantis values below 2000 meters were between 5.5 and 6 ml per liter: the Carnegie values were 6.09 ml per liter.

The series obtained at Carnegie station 8 (latitude 63° 30′ north, longitude 14° 41′ west) is interesting as it shows conditions in high latitudes where there is no thermal stratification of the water. It is thus evident from the available data that at this station the quantity of oxygen is nearly uniform from the surface to the bottom, the quantity being about 6 ml per liter.

In the Atlantic the stratosphere contains considerably more oxygen than it does in the Pacific. Wattenberg (1929) states that the high oxygen content of the deep water of the Atlantic can be accounted for by the fact that this water originates in the polar and subpolar regions and that at great depths very little oxygen is consumed.

As shown in table C4 the oxygen content of the deep water of the Pacific is decidedly below that at the surface. The highest value obtained in the central Pacific was 3.87 ml per liter at 3900 meters at station 161, northeast of the Samoan Islands. It is thus evident that the deep water of the central and eastern Pacific has lost a much larger part of its original oxygen than has the deep water in the Atlantic. From this it must be concluded that, since there is probably no significant difference between the two oceans in the rate of oxygen consumption, the deep water in the Pacific has lacked contact with the atmosphere for a longer period than has the Atlantic deep water, either because the Pacific water flows at a slower rate or is farther removed from its sinking center.

In this connection it is interesting to note that, as shown in the other papers accompanying this report, present knowledge indicates that the deep water of the Pacific is richer in phosphate and silicate and has a lower pH, which means a higher carbon dioxide content, than that of the Atlantic. These are further indications that the deep water of the Pacific has lacked contact with the surface layer for a greater length of time than has the water of the Atlantic.

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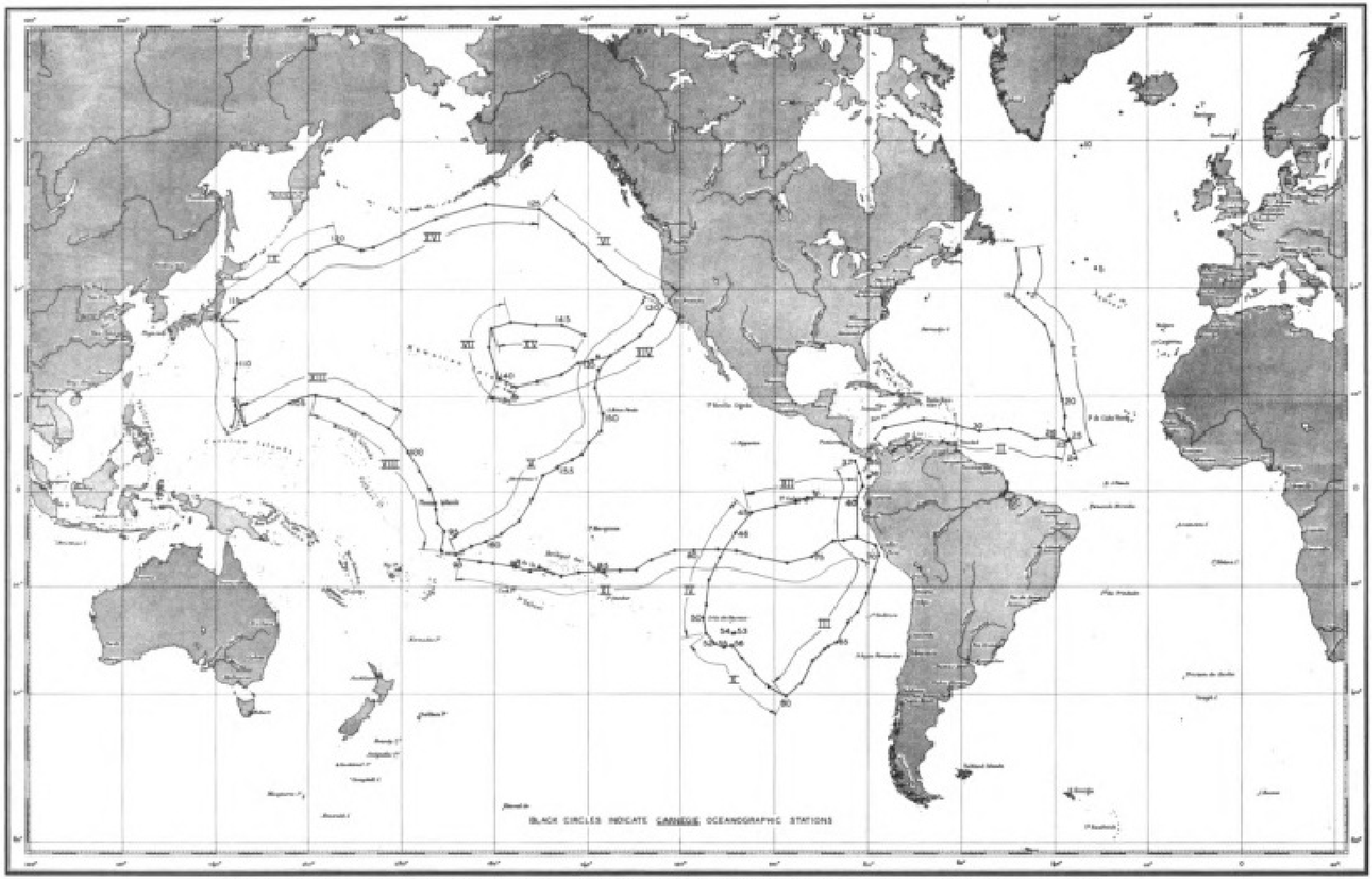


FIG. C1—STATIONS AND VERTICAL SECTIONS, CHEMICAL DATA, ATLANTIC AND PACIFIC OCEANS, FROM *CARNEGIE* RESULTS, 1928-1929

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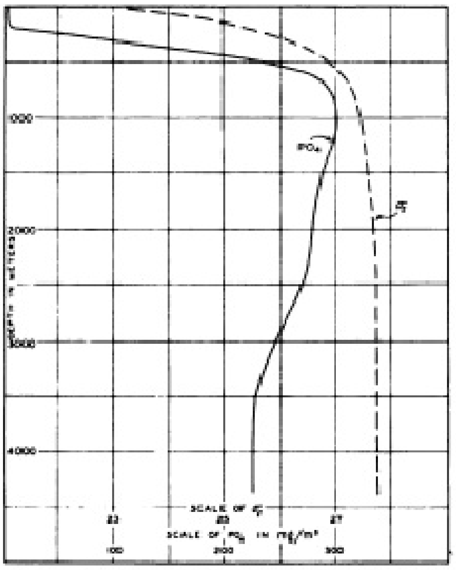


FIG. C2—VERTICAL DISTRIBUTION PHOSPHATE AND DENSITY AT CARNEGIE STATION 137 (24° 02' NORTH, 145° 33' WEST)

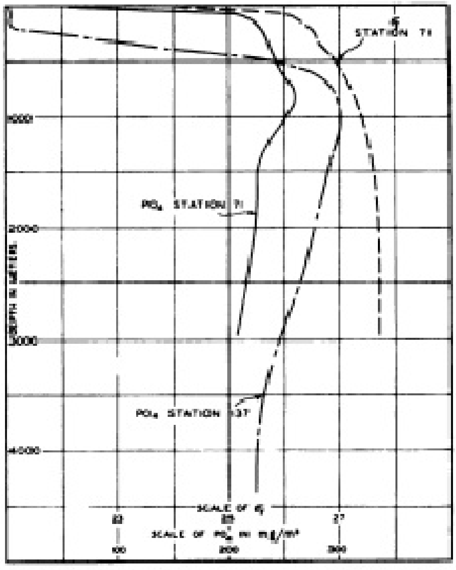


FIG. C3—VERTICAL DISTRIBUTION PHOSPHATE AND DENSITY AT CARNEGIE STATION 71 (11° 57' SOUTH, 78° 37' WEST) AND PHOSPHATE AT CARNEGIE STATION 137 (24° 02' NORTH, 145° 33' WEST)

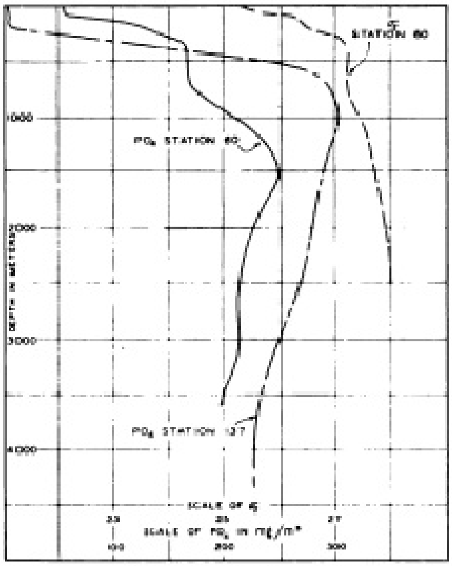


FIG. C4—VERTICAL DISTRIBUTION PHOSPHATE AND DENSITY AT CARNEGIE STATION 60 (40° 27' SOUTH, 97° 33' WEST) AND PHOSPHATE AT CARNEGIE STATION 137 (24° 02' NORTH, 145° 33' WEST)

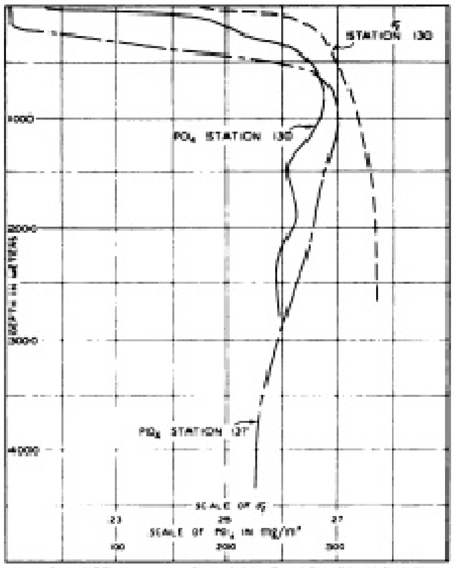


FIG. C5—VERTICAL DISTRIBUTION PHOSPHATE AND DENSITY AT CARNEGIE STATION 130 (37° 05' NORTH, 123° 43' WEST) AND PHOSPHATE AT CARNEGIE STATION 137 (24° 02' NORTH, 145° 33' WEST)

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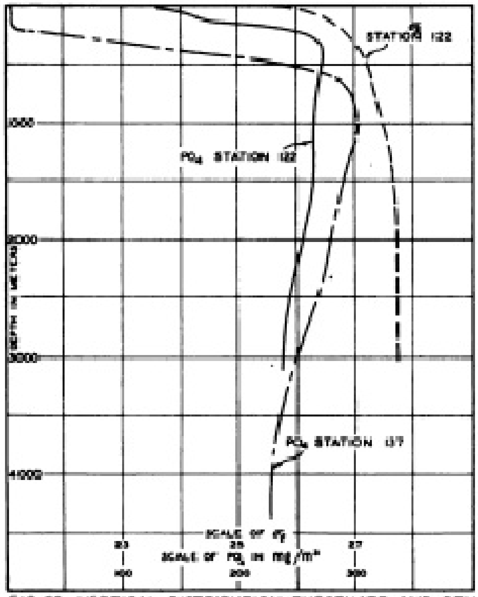


FIG. C6—VERTICAL DISTRIBUTION PHOSPHATE AND DENSITY AT *CARNEGIE* STATION 122 (46° 16' NORTH, 174° 03' EAST) AND PHOSPHATE AT *CARNEGIE* STATION 137 (24° 02' NORTH, 145° 33' WEST)

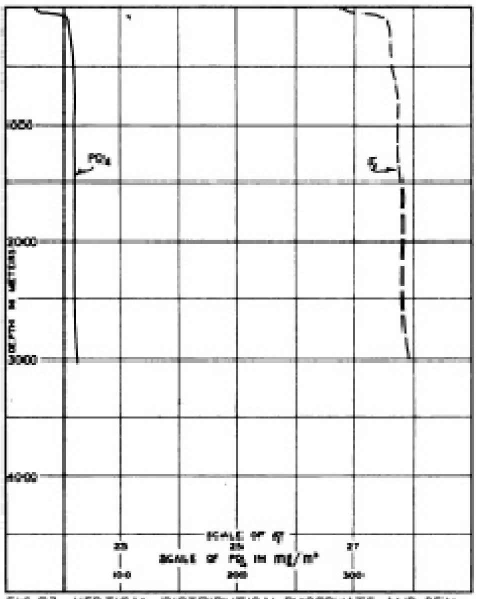


FIG. C7—VERTICAL DISTRIBUTION PHOSPHATE AND DENSITY AT *CARNEGIE* STATION 10 (59° 19' NORTH, 34° 15' WEST)

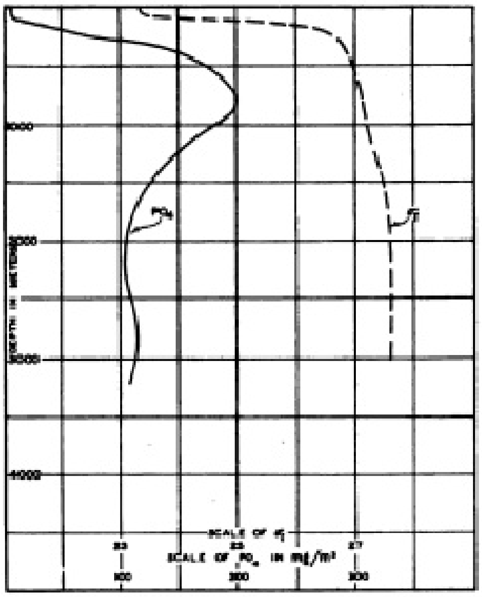


FIG. C8—VERTICAL DISTRIBUTION PHOSPHATE AND DENSITY AT *CARNEGIE* STATION 29 (13° 16' NORTH, 52° 13' WEST)

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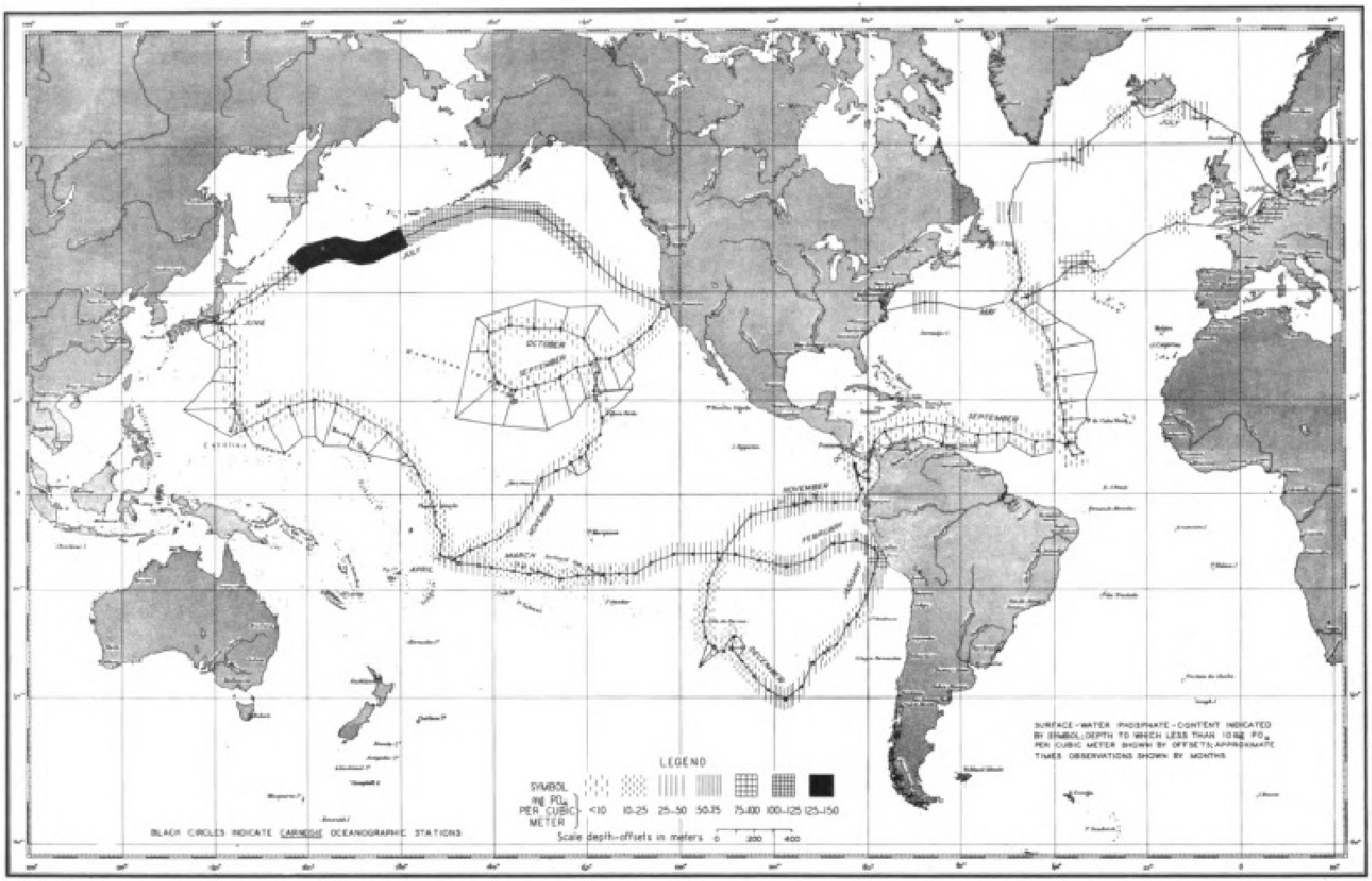


FIG. C9—RELATIVE PHOSPHATE CONCENTRATION SURFACE WATER AND DEPTHS TO WHICH LESS THAN 10 mg PO_4 PER CUBIC METER OCCUR, CARNEGIE RESULTS, 1928-1929

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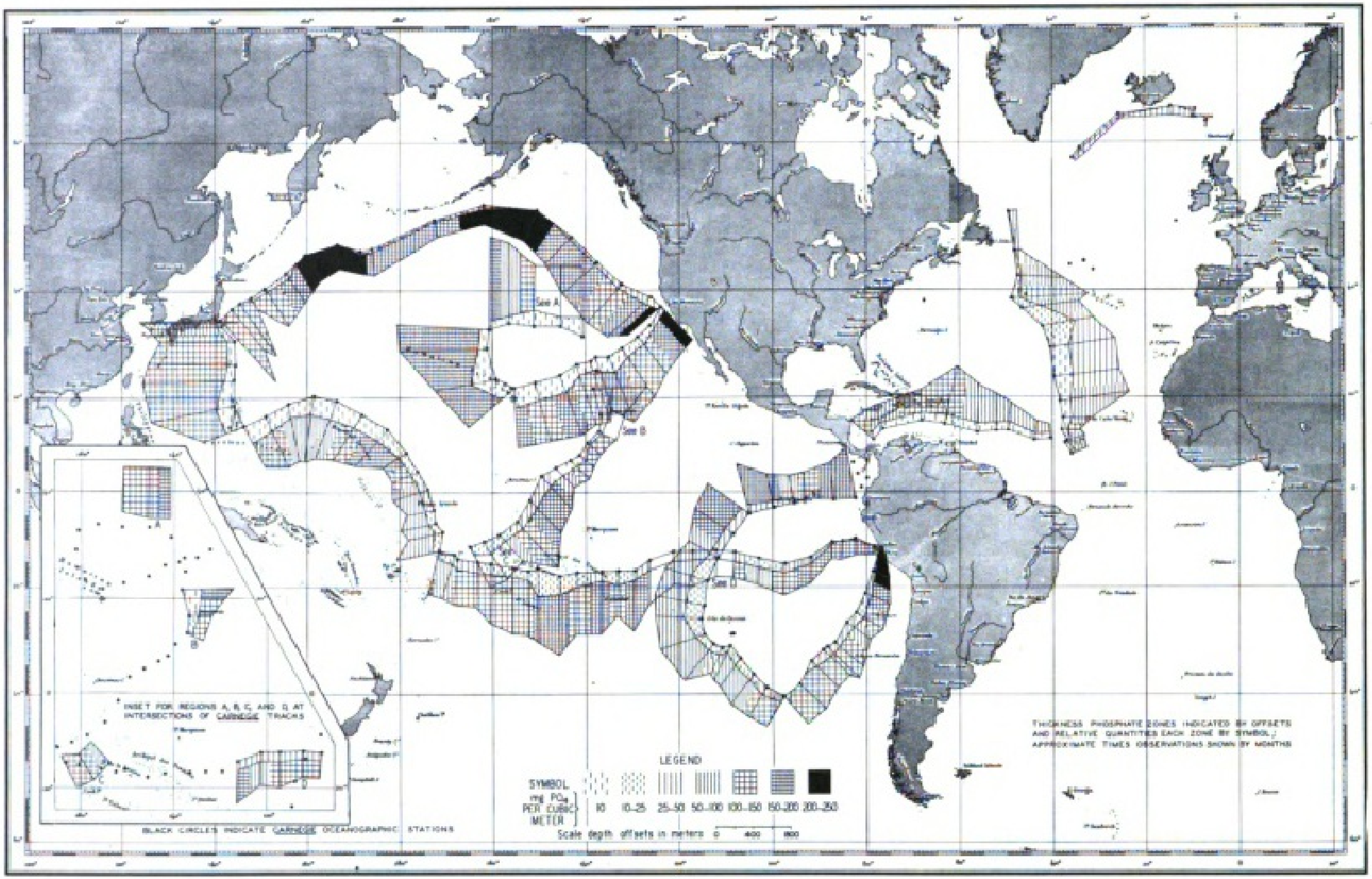


FIG. C10—THICKNESS PHOSPHATE CONCENTRATION SURFACE LAYER AND TRANSITION ZONE AND RELATIVE QUANTITIES EACH ZONE, CARNEGIE RESULTS, 1928-1929

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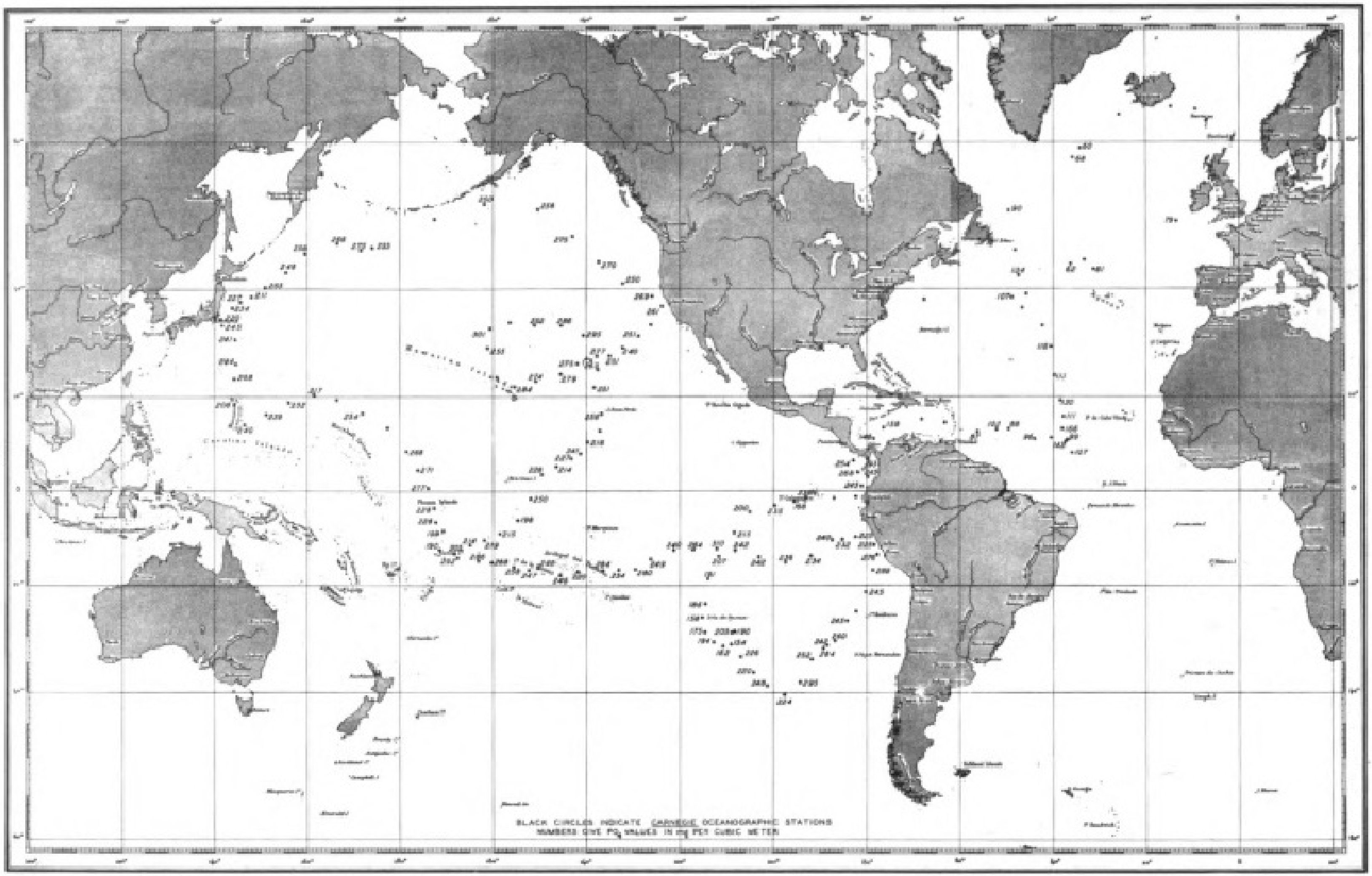


FIG. CII—PHOSPHATE CONCENTRATION AT 2000 METERS, CARNEGIE RESULTS, 1928-1929

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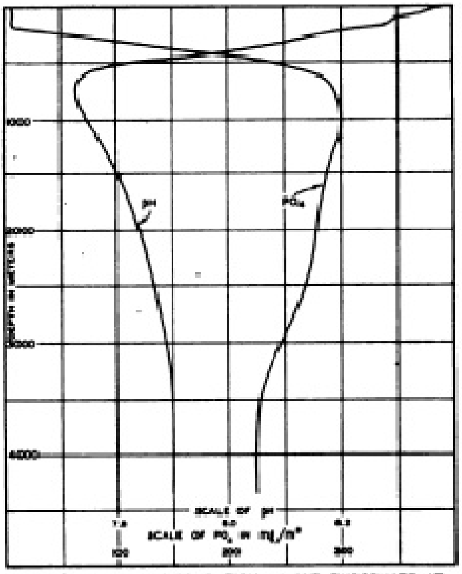


FIG. C12—VERTICAL DISTRIBUTION pH AND PHOSPHATE AT *CARNEGIE* STATION 137 (24°02′ NORTH, 145°33′ WEST)

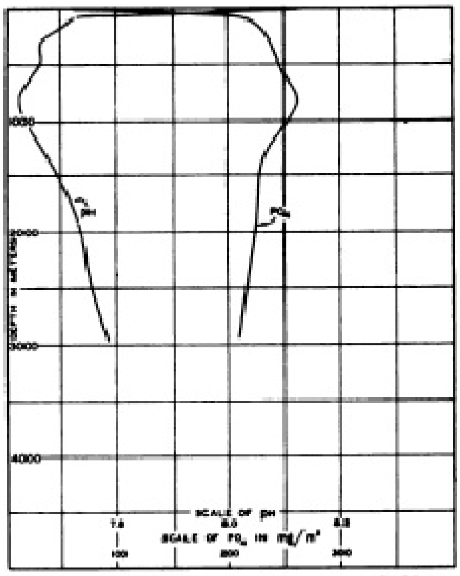


FIG. C13—VERTICAL DISTRIBUTION pH AND PHOSPHATE AT *CARNEGIE* STATION 71 (11°57′ SOUTH, 78°37′ WEST)

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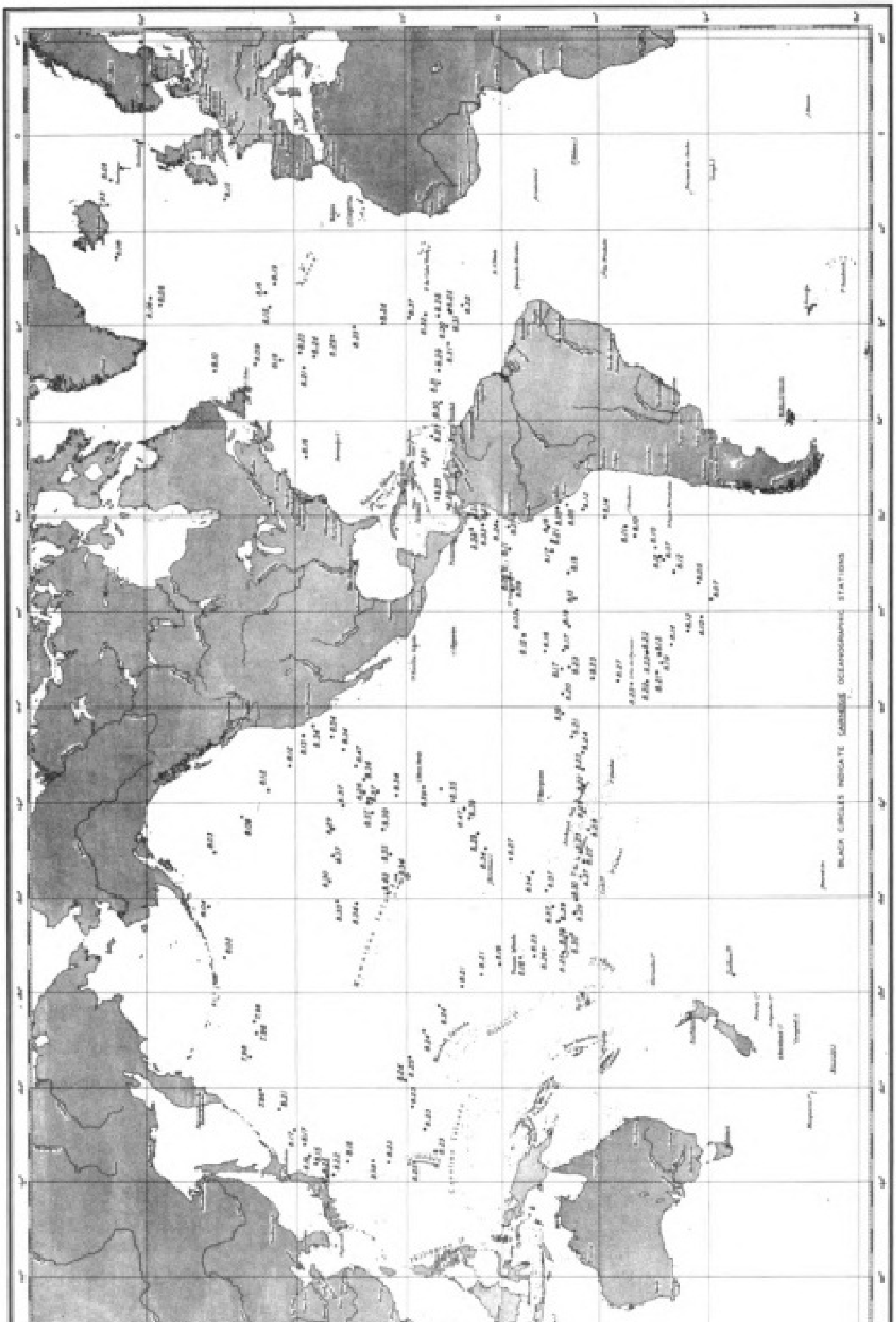


FIG. C14—HORIZONTAL DISTRIBUTION HYDROGEN-ION CONCENTRATION AT SURFACE, FROM CARNEGIE RESULTS, 1928-1929

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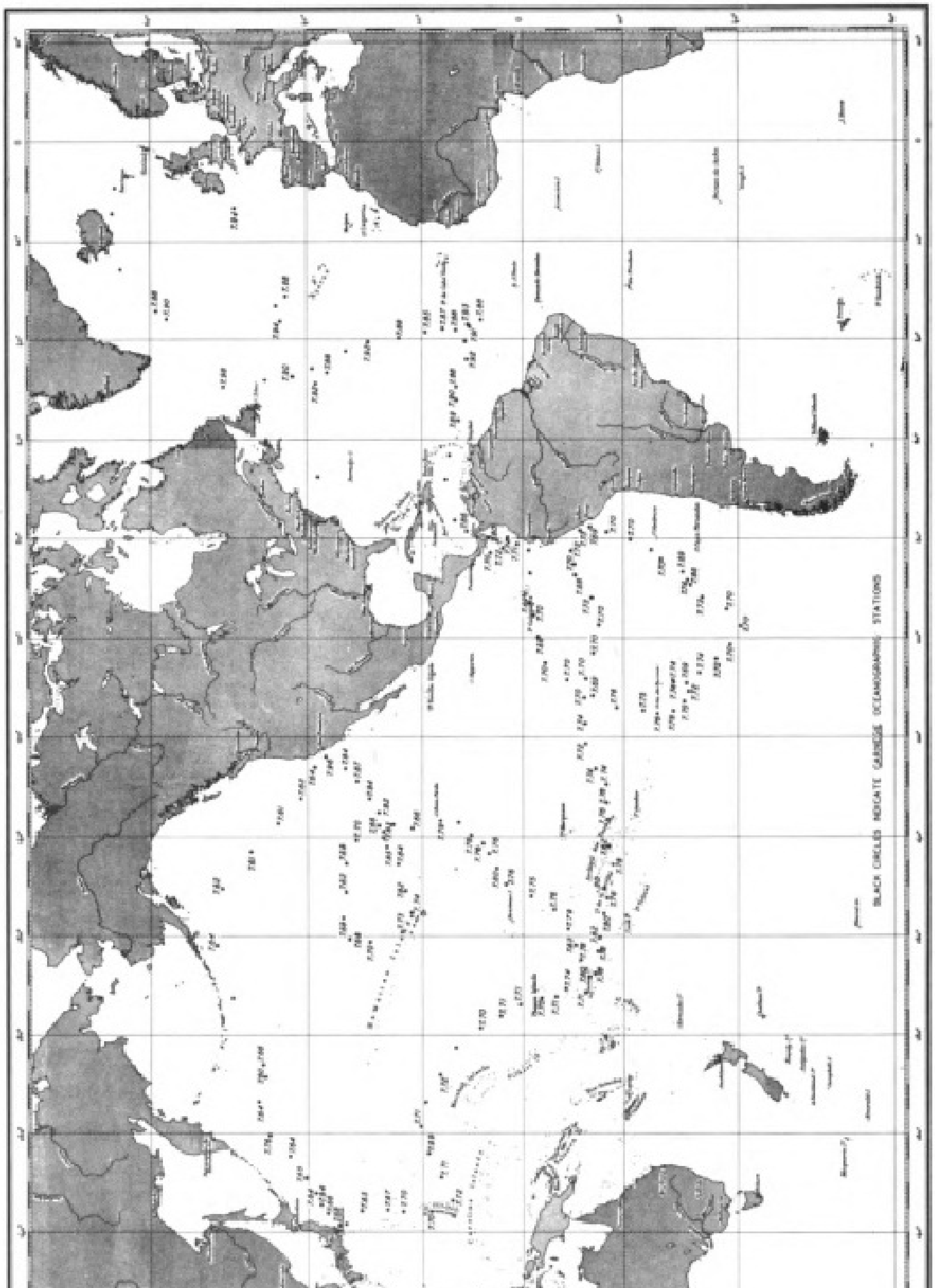


FIG. C15—HORIZONTAL DISTRIBUTION HYDROGEN-ION CONCENTRATION, 2000 METERS, FROM CARNEGIE RESULTS, 1928–1929

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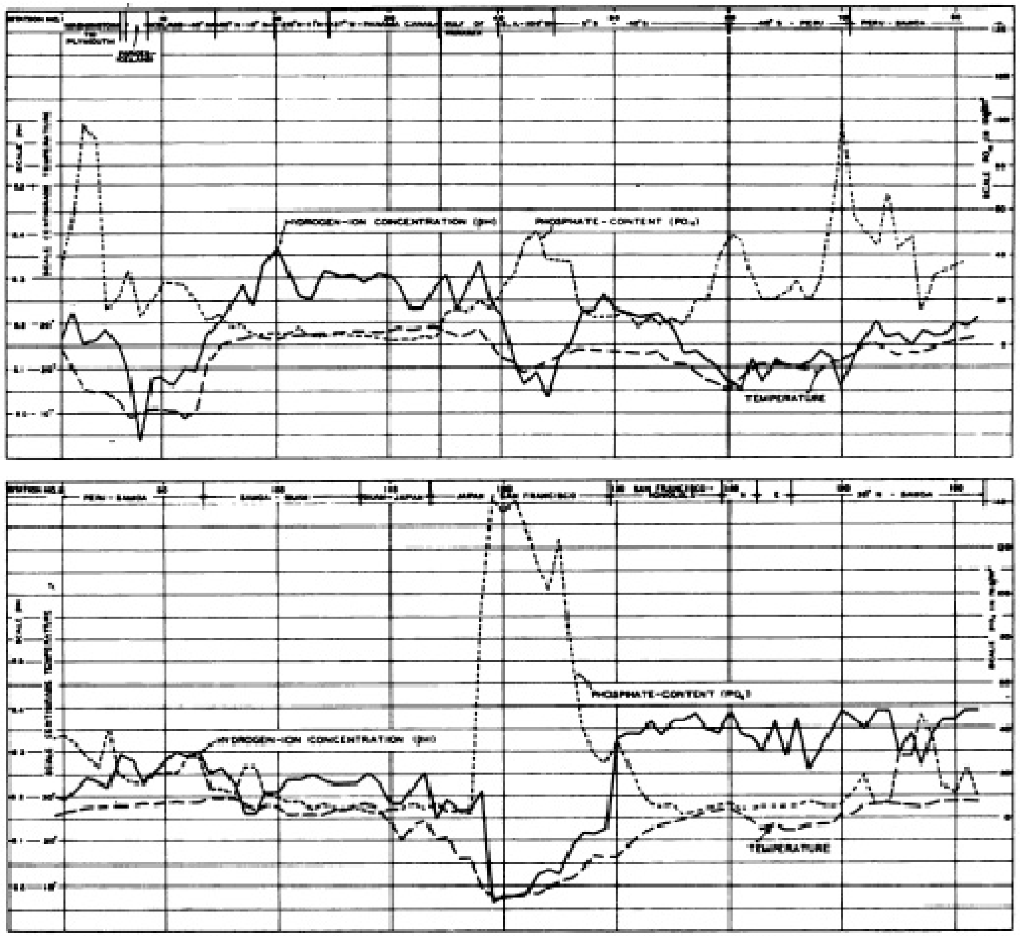


FIG. C16—PHOSPHATE-CONTENT, HYDROGEN-ION CONCENTRATION, AND TEMPERATURE SURFACE-WATER, CARNEGIE STATIONS, 1928-1929

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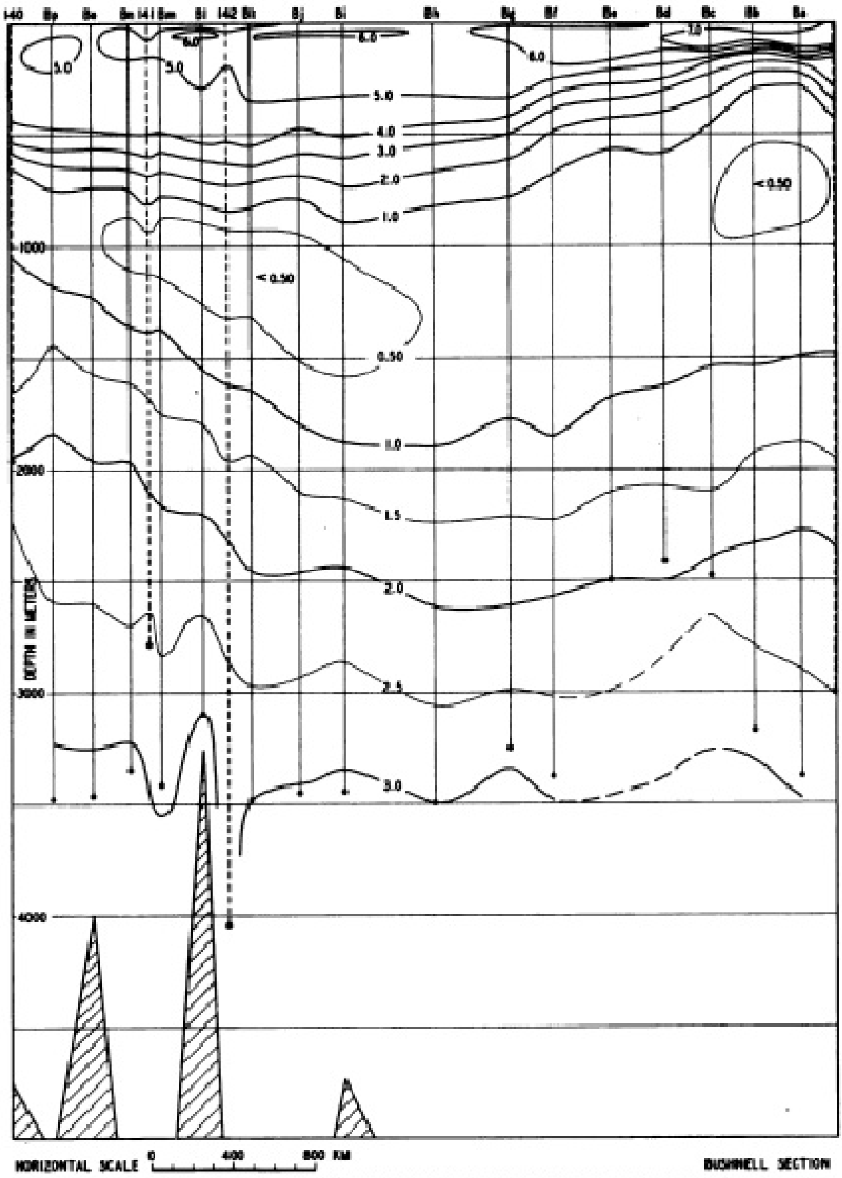


FIG. C17—DISTRIBUTION OF OXYGEN BETWEEN ALEUTIAN ISLANDS AND HAWAII, FROM BUSHNELL, AUGUST 1934

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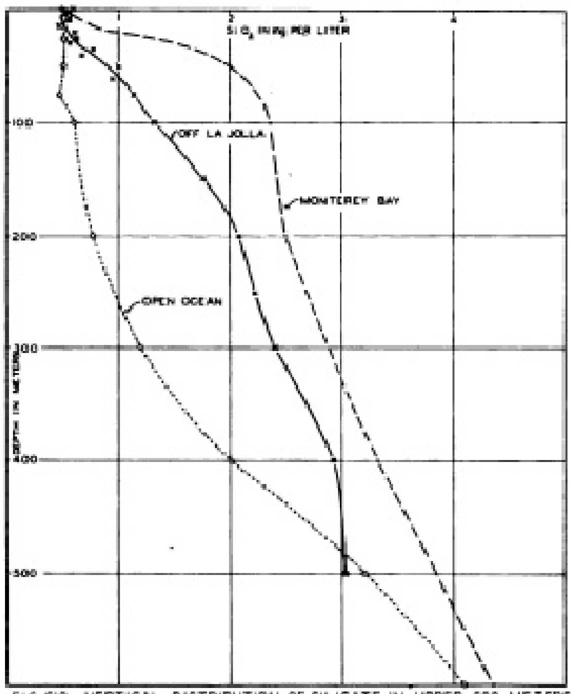


FIG. C18—VERTICAL DISTRIBUTION OF SILICATE IN UPPER 600 METERS AT MONTEREY BAY (AFTER BIGELOW AND LESLIE, 1930), OFF LA JOLLA (FROM UNPUBLISHED DATA BY MOBERG), AND IN OPEN PACIFIC (CARNEGIE DATA). CARNEGIE CURVE IS MEAN OF 16 VERTICAL SERIES OF OBSERVATIONS MADE NORTH OF 20° NORTH LATITUDE

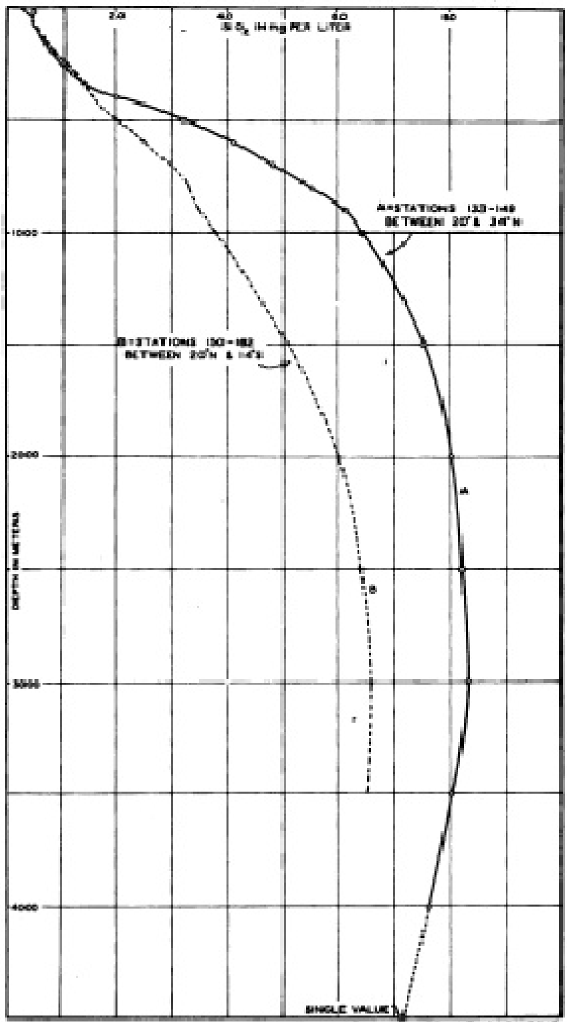


FIG. C19—MEAN VERTICAL DISTRIBUTION OF SILICATE AT CARNEGIE STATIONS NORTH OF 20° NORTH AND AT STATIONS SOUTH OF 20° NORTH

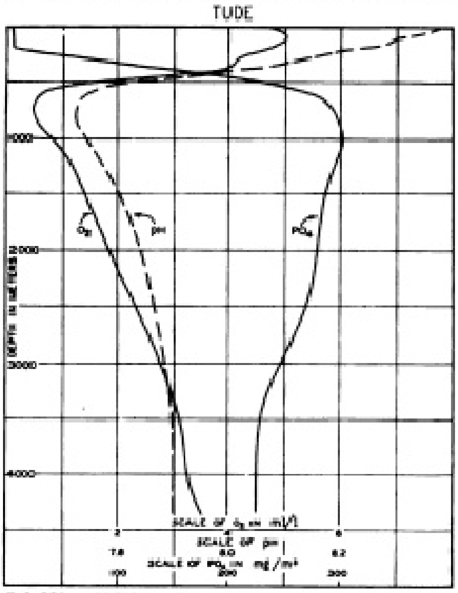


FIG. C20—VERTICAL DISTRIBUTION OXYGEN, PHOSPHATE, AND pH AT CARNEGIE STATION 137 (24°02' NORTH, 145°33' WEST)

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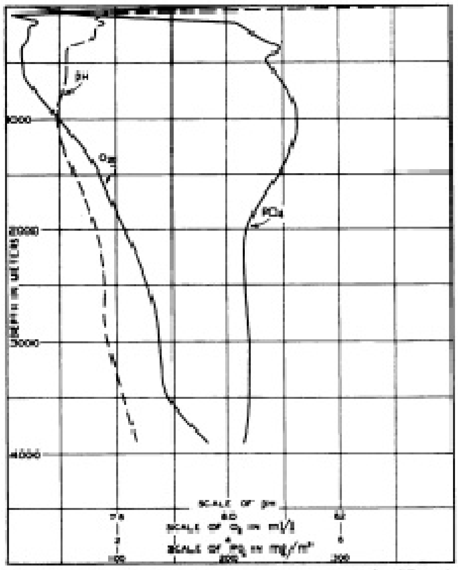


FIG. C21—VERTICAL DISTRIBUTION OXYGEN, PHOSPHATE, AND pH AT CARNEGIE STATION 152 (10°05′ NORTH, 139°44′ WEST)

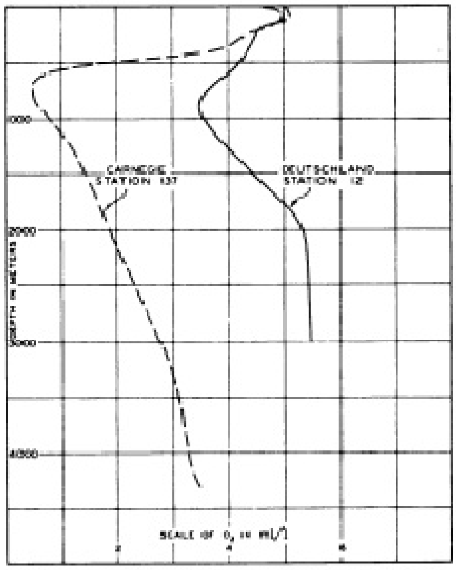


FIG. C22—VERTICAL DISTRIBUTION OXYGEN AT CARNEGIE STATION 137 (24°02′ NORTH, 145°33′ WEST) AND AT DEUTSCHLAND STATION 12 (27°46′ NORTH, 27°36′ WEST)

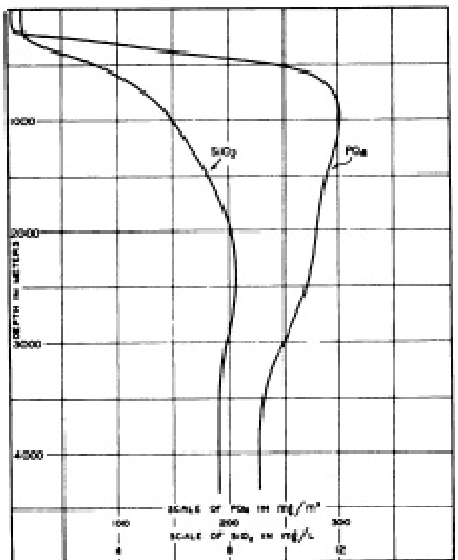


FIG. C23—VERTICAL DISTRIBUTION PHOSPHATE AND SILICATE AT CARNEGIE STATION 137 (24° 02′ NORTH, 145°33′ WEST)

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